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ADDENDUM
TO
R–977

INTERIM INFORMAL REPORT ON
WORK COMPLETED
ON STANDARDIZED SOFTWARE DEVELOPMENT

MAY – AUGUST 1976

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The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER R-977	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) INERTIAL NAVIGATION SYSTEM STANDARDIZED SOFTWARE DEVELOPMENT, FINAL TECHNICAL REPORT, ADDENDUM	5. TYPE OF REPORT & PERIOD COVERED 3/15/76-4/30/76
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. Sciegienny, R. Nurse, J. Wexler, P. Kampion	8. CONTRACT OR GRANT NUMBER(s) F33615-75-C-1149
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Charles Stark Draper Laboratory, Inc. 63 Albany Street Cambridge, Massachusetts 02139	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task 4.2.1
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Avionics Laboratory Wright-Patterson Air Force Base Dayton, Ohio 45433	12. REPORT DATE June 1976
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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A	23	

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Inertial Navigation
Computer Algorithms
Computation Errors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A navigation software simulation program was developed, checked and verified as a part of an investigation into the feasibility of standardization of software for aircraft Inertial Navigation Systems (INS). The program can be used to simulate the unaided INS navigation errors resulting from a particular mechanization of the navigation equations on a given digital computer.

Technical data required for the Simulator Program design was obtained from survey of typical INS navigation software. The survey results revealed

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20. Abstract (continued)

commonality in navigation computations employed in various INS configurations, the gravity models approximations used in the computations, the commonality in the frames and the transformations symbology employed in the computations and the software interface between the INS computations and the Avionics-System computations.

The navigation software simulation program is coded in Fortran IV for use on either IBM-360 or CDC-6600 computers.

The report is comprised of four volumes:

Volume I Introduction and Summary

Volume II INS Survey and Analytical Development

Volume III Program Description and User's Guide

Volume IV Program Listings

Addendum

ADDENDUM

TO

R-977

INTERIM INFORMAL REPORT ON WORK COMPLETED ON STANDARDIZED SOFTWARE DEVELOPMENT

by

R. Nurse

J. Wexler

MAY - AUGUST 1976

The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

FOREWORD

This addendum to Draper Laboratory Report R-977, Inertial Navigation System Standardized Software Development, is the first in a series of informal memos documenting work completed since May, 1976. For convenience it has been published and bound with a cover.

Four topics are documented after a short background:

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ACKNOWLEDGEMENT

This four-volume report was prepared under USAF Contract F33615-75-C-1149 by Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts, in accordance with Section 4 of the contract. The monitoring Air Force project engineer is Captain E. Harrington (RWA-2), Air Force Avionics Laboratory, Dayton, Ohio.

The Draper Laboratory Program Manager for this task is Dr. George T. Schmidt and the Lead Engineer is Arthur Ciccolo. The coordinator of this report is Janusz Sciegienny and the authors are Janusz Sciegienny, Roy Nurse, Peter Kampion and John Wexler.

The authors express their appreciation to Mr. W. Shephard, Mr. D. Kaiser and Mr. Stan Musick of the Air Force Avionics Laboratory for their assistance during the course of this contract.

SHORT TERM FOLLOW-ON
TO STANDARD SOFTWARE PROGRAM

(MAY - JULY 1976)

Background

By the end of April 1976, the Numerical Simulator, NUMSIM program had been checked out and was running (with AFAL's Profile Generator program, PROFGEN) on the AFAL CDC 6600. The final report had been rough drafted and was submitted to documentation.

However, the need for some modifications to PROFGEN and hence to NUMSIM, were evident. In addition, some post-processing programs were needed for efficient use of the PROFGEN/NUMSIM package, and a short parametric study, and some long runs with representative hardware/software configurations were desired.

The short term follow-on efforts were directed towards fulfilling these objectives (as specified in a Statement of Work and Task Breakdown).

Summary

1) AFAL modified PROFGEN to compute and output the integrals of specific force, in each of the local vertical, space stable, and strapdown frames - rather than the specific forces per se as had been provided previously.

2) CSDL modified NUMSIM to accept these integrals rather than instantaneous values of specific force with subsequent (approximate) integration as had previously been the case.

3) NUMSIM was modified to compute the sum of the squares of the errors over its output cycle time. This provided the capability of generating short or long term rms errors in post-processing programs (in addition to instantaneous errors).

4) A plotting program, to provide the capability of generating CALCOMP plots of any of the errors in (3), was added.

5) Checkout runs employing the modified PROFGEN and NUMSIM programs indicated that the errors in NUMSIM outputs for gimballed systems (local vertical or space stable) could be made arbitrarily small. Small errors in strapdown system outputs occur principally due to discontinuities (steps) in the angular rates between PROFGEN outputs.

6) The variable precision version of NUMSIM VUMSIM was checked out on the CDC 6600.

7) A short parametric study was performed to obtain preliminary estimates of the sensitivities of system performance to changes in hardware/software configuration.

8) Long runs were performed using the same mission profile and hardware configuration but varying only the software. Generally, the simpler (or "baseline") software was shown to be adequate for a moderate accuracy, aircraft INS. An anomaly in the performance of the "upgraded" software during benign flight conditions led to continued investigations during July.

9) The investigation revealed that a 24-bit mantissa was not adequate for the position computations (direction cosine matrix, update, orthonormalization) in an accurate INS. The mantissa was extended for these computations-to-simulate-32-bit, fixed point computations. This eliminated the anomaly. (A similar precision extension would be useful in the velocity summing computations.) Sign errors (in both PROFGEN and NUMSIM) on one component of gravity were corrected.

10) More detailed descriptions of the short term follow-on efforts and results are presented in the body of this report.

I. Changes Made to Simulator

A. Used revised TAPE20 input and input format as follows:

i) Expanded "TRAJIN" COMMON block in all routines to include the three sets of specific forces. These values are stored in the SFIS array as indicated on 'Revised TAPE20 Format'.

ii) Block data routine modified to initialize SFIS to zero.

iii) INREC routine modified to read the updated (23 word) records.

iv) CMINTG was modified so that when IPC(24) is not equal to zero, the delta velocities are found by summing the PROFGEN specific force integrals, as picked up from SF$T.

v) Changes were made to SSINTG, LLINTG, and SDINTG so that when IPC(24) is not equal to zero, each routine

a) picks up information about the integral of specific force from SFIS,
b) corrects it to NUMSIM frame, misaligning it (if appropriate) for the local level case, and
c) stores it in SF$T for use by CMINTG.

B. Generated statistics and wrote them (using revised TAPE30 output format) and printed them as follows:

i) Executive was modified so that at the end of each navigation cycle

a) OUTUNI was called,
b) If IPC(22) is not equal to zero, a new subroutine SSQALL is called.

ii) A new COMMON block SUMSQS was added to Block Data, PLTAPE, PRINTR and SSQALL. The block contains SUMSQ1(10) and SUMSQ2(10). SUMSQ1 contains the sums of the squares of the difference,(between PROFGEN and NUMSIM at the end of navigation cycles), since the beginning of the NUMSIM run. The differences are of the following ten items in this order:

1.	Latitude	- degrees
2.	Longitude	- degrees
3.	Alpha	- degrees
4.	Altitude	- feet
5.	Velocity up	- feet/sec
6.	Velocity east	- feet/sec
7.	Velocity north	- feet/sec
8.	Roll	- degrees
9.	Pitch	- degrees
10.	Heading	- degrees

SUMSQ2 has the sum of the squares as above, only accumulated since the last tape output.

iii) Output COMMON block was redone so that DLAT, DLONG, DALF, DH, DV(3), DETA(3) appear in the order shown in this sentence.

iv) PRINTR was expanded so that when IPC(22) is not equal to zero, the square roots of the values in SUMSQ1 are printed out.

v) PLTAPE was expanded so that it writes out information in the new TAPE30 format, which implies taking the mean of the values in SUMSQ2, writing out the mean, and then clearing SUMSQ2.

C. <u>Miscellaneous Cleanups, Corrections and Improvements</u>

1) In the exec, PTIME and PLTIME were added to the SIMPAR NAMELIST. This was done to allow easier control over starting both printout and tape output.

2) PRINTER and PLTAPE were fixed to agree with the current initialization scheme. PLTAPE was changed to "rewind" its output file during initialization.

3) A test for STH equal to zero was added to SDATUD to prevent a possible division by zero.

Revised "TAPE30" Format

Record	Length			Contents
1	10			40 character title, stored four characters per word
2-n	21		1)	time, in seconds
			2)	Δ latitude
			3)	Δ longitude
		where Δ is	4)	Δ alpha
		difference, at	5)	Δ altitude
		'time'seconds,	6)	Δ velocity (up)
		between PROFGEN	7)	Δ velocity (east)
		and NUMSIM;	8)	Δ velocity (north)
			9)	Δ roll
			10)	Δ pitch
			11)	Δ heading
		and where Σ is the	12)	Σ latitude
		mean sum of the	13)	Σ longitude
		squares of the	14)	Σ aplha
		differences (at	15)	Σ altitude
		the end of each	16)	Σ velocity (up)
		navigation cycle)	17)	Σ velocity (east)
		between PROFGEN	18)	Σ velcoity (north)
		and NUMSIM,	19)	Σ roll
		<u>since</u> the last	20)	Σ pitch
		tape output.	21)	Σ heading

Revised "TAPE20" Format for PROFGEN Output

Record #	Contents
1	Unmodified
2	Unmodified
3	Unmodified
4-n	Words 1 - 14 are unmodified words, 15-23 are integrals (over the output period) of specific force as follows:

15) North component (for $\alpha = 0$)
16) West
17) Up

Local Level

18) Forward
19) Right Wing
20) Down

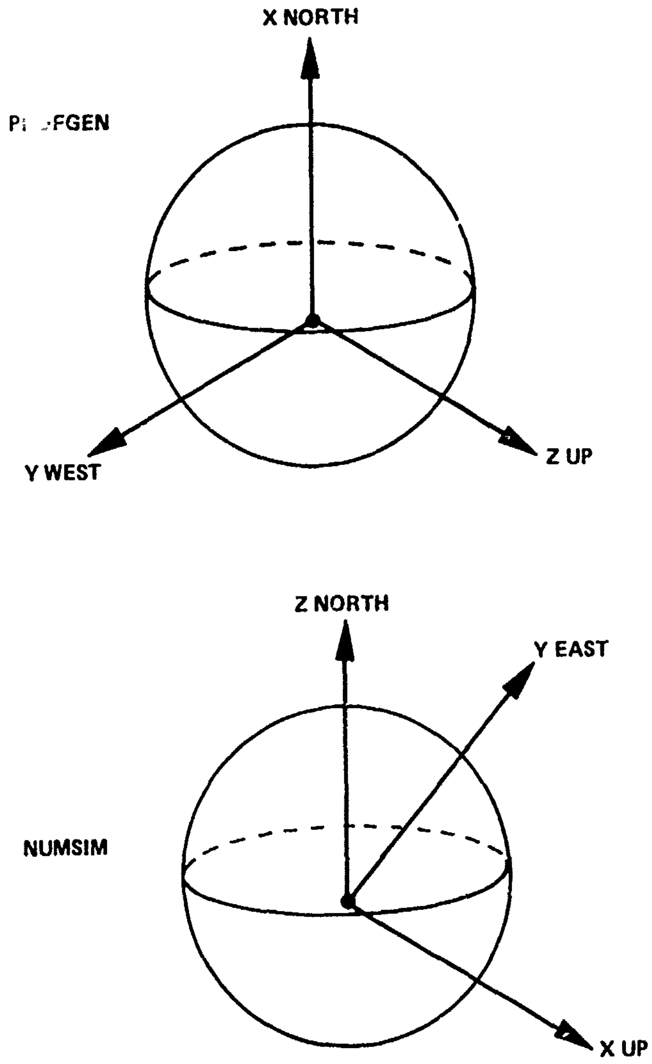
Strapdown

21) North
22) West
23) Up

Space Stable

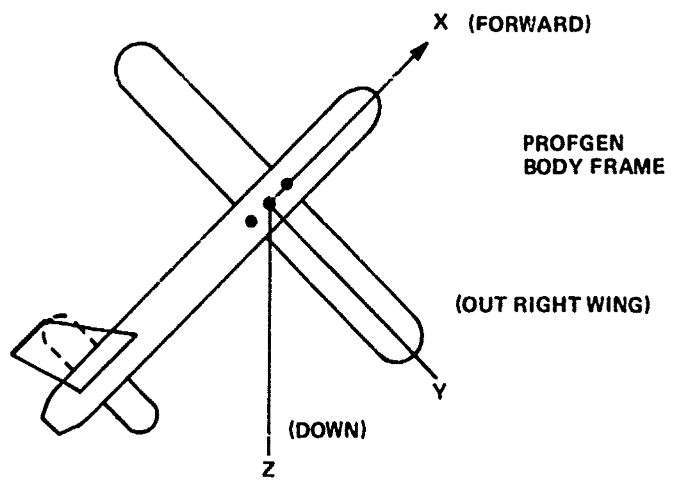
The fol:owing two pages define the PROFGEN and NUMSIM coordinate conventions.

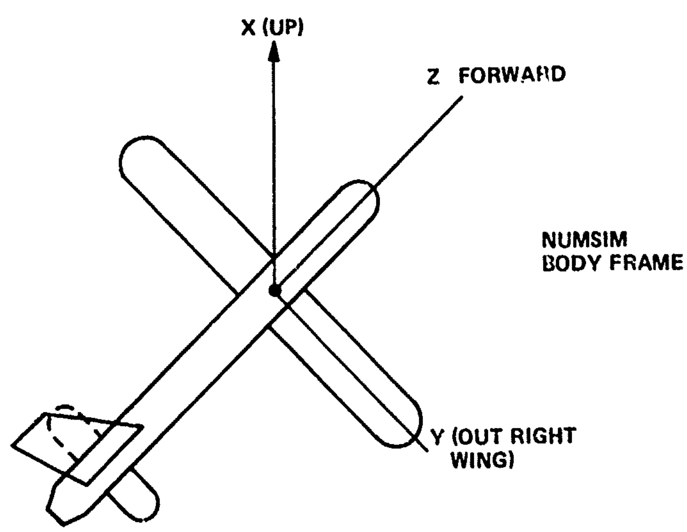
SPACE STABLE FRAMES



SPACE STABLE FRAMES

STRAPDOWN FRAMES





D. Changes to NUMSIM to implement more precision in DCMUPD and ORTHO

```
1362          WRITE (6,691)
1364 691      FORMAT ("b THIS VERSION HAS GREATER PRECISION",
1366          IN DCMUPD AND ORTHO"/"b AND ASSUMES FRACTL (=40')

10092         COMMON(PRECIS)FRACTL, EXPO
10094         INTEGER FRACTL, EXPO
10675         FRACTL = FRACTL+8
10745         FRACTL = FRACTL-8
10755         FRACTL = FRACTL+8
10765         FRACTL = FRACTL-8
14542         COMMON/PRECIS/FRACTL, EXPO
14544         INTEGER FRACTL, EXPO
14555         FRACTL = FRACTL+8
14625         FRACTL = FRACTL-8
```

E. Fix to "North component of gravity" (actually projection of this onto $\hat{y}$ axis in LLWA frame). In subroutine GRAV change

```
G$2P(2) = -COEF*AØP$2P(3,2)
                to
G$2P(2) =  COEF*AØP$2P(3,2)
```

II Changes Made to PROFGEN

a) By AFAL; calculations of integrals of specific force (Note that IRITE must be 1 for printed output to be correct).

b) By CSDL; took out

```
CALL ACCLRTN (FX, FY, FZ)
```

at lines 11620 and 14400.

III. Summary of Short Parametric Study

Fifteen 8-second runs were performed to gain some insight into the sensitivity of the navigation errors to:

a) word length

b) navigation computation cycle

c) algorithm "order"

d) quantization

The first three runs, sequence numbers 1, 2, and 3, used the baseline software with coarsest quantization, a 1/8 second navigation computation cycle, and the full precision word (corresponding to 48-bit mantissa) and represented a strapdown (SD), a local vertical (LV), and a space stable (SS) inertial measuring unit (IMU) respectively.

The next three runs, sequence numbers 4, 5, and 6, differed from the first three only in the reduction of the mantissa (fractional part) of the word length to 24 bits.

The next three runs, sequence numbers 7, 8 and 9, all employ the higher order algorithm, with the full word length and no quantization, for a LV IMU. They differ only in the frequency of navigation computations, 128, 32, and 8 times a second.

The next three runs, sequence numbers 10, 11, and 12, employ the higher order algorithm, with full wordlength, 8 Hz navigation computations for a LV IMU with coarse, moderate and fine quantization of incremental velocity and gimbal angles. The values of VQUANT are 0.04, 0.01, and 0.0025 feet per second per pulse, while the corresponding values of AQUANT are 0.384, 0.096, and 0.024 milliradians respectively.

The final three runs, sequence numbers 13, 14, and 15, are all 8 Hz, LV IMU cases with full word length and no quantization. They differ only in the portions of the higher order algorithm included, which latter are controlled by the flags, IPC (28), IPC (29), and IPC (30). With all 3 flags set to zero (Seq. #13) the baseline algorithm is mechanized. With IPC(30) = 1, (Seq. #14) the exact expression for angular velocity replaces the approximate expression used in the baseline case. With IPC(29) = IPC (30) = 1, the interpolation, extrapolation and change of flow of the upgraded algorithm is added to previous case. The resultant is the higher order algorithm with the exception that a first order direction cosine matrix update is performed.

RESULTS OF RUNS, SEQUENCE NOS. 1 THROUGH 15

In most cases, the output of each run was displayed on the CRT of the Hazeltine 2000 (72 columns), and printed out on the 80 column satellite roll type printer. This process was rather tedious and the resulting formats were ungainly compared with the normal line printer outputs - so these printouts are not included.

In some cases, Calcomp plots were produced and are included. A complete set of plots consists of three sets of ten plots each representing the instantaneous, the rms values (between output intervals and the time rms (from start of run to indicated output time) of each of the following navigation errors:

- latitude, longitude, wander angle (in degrees)
- altitude (in feet)
- up, east, and, north velocity (in feet per second)
- roll, pitch, and heading (in degrees)

The more significant results of the short parametric study are summarized in Tables 1 through 6 in declining order of importance (for the particular 8 second simulated flight). Note that only the rms errors at the end of the runs are compared.

Calcomp plots of the instantaneous errors from a strapdown run preceding Sequence #1 are shown in plots #1 through 10. This represents best available strapdown performance (with the present PROFGEN dynamics). Hand plots of the east and north velocity errors, every 1/128th of a second, are included to illustrate the error build-up during the 1/2g turn.

Calcomp plots of the short term runs ("average") errors from the sequence #1 "baseline" strapdown run are shown in plots #13 through 22.

Hand plots of the rms east velocity errors during the sequence #1, 2, 3 runs show the velocity errors approaching the asymptotes expected due to incremental velocity quantization (plot #25).

Table 1

Comparison of Time RMS Errors
at End of 8 Sec., 8 Hz LV Runs
- Effects of Algorithm, Quantization, Word Length
Ideal vs. Baseline

Error Type	Units	Magnitude		Ratio #5/#9
		Ideal Seq.#9	Baseline/wQ. Seq.#5	
Long.	μ deg.	.00242	8.827	3640
Lat.	μ deg.	.0125	16.46	1320
Alt.	feet	.00241	.6384	254
V east	mfps	.0110	19.13	1740
V north	mfps	.0138	21.89	1590
V up	mfps	.0677	21.47	317
Roll	μ deg.	.0822	4.034	49,000
Pitch	μ deg.	.6734	10.525	15,700
Heading	μ deg.	.0017	16.063	9,450,000

Table 2

<u>Comparison of Time RMS Errors</u>

<u>at End of 8 Sec, 8 Hz, LV Runs</u>

Ideal vs. Baseline Algorithms

(No quantization)

Error	Units	Ideal (Seq.#9)	Baseline (Seq.#13)	Ratio #13/#9
*Long.	μ deg	.00242	11.18	4650
Lat.	μ deg	.0125	.6310	51
Alt.	feet	.00241	.6153	255
V east	m feet/sec	.0110	.1152	10.4
V north	m feet/sec	.0138	.1611	11.7
V up	m feet/sec	.0677	2.946	43.4
Roll	μ deg	.0822	.6175	7.5
Pitch	μ deg	.6734	8.438	12.5
Heading	μ deg	.0017	7.908	4650

*Velocity error during 1st sec of east acceleration causes 11.6 μ deg longitude error.

Table 3

Comparison of Time RMS Errors
at End of 8 Sec. LV Runs
vs. Navigation Comp. Cycle

Error Type	Units	Nav. Comp. Cycle (Hz) 128 Seq.#7	32 Seq.#8	8 Seq.#9	Ratios #8/#7	#9/#8
*Long.	µ deg.	.000007	.000139	.002424	19.9	17.4
Lat.	µ deg.	.000166	.000742	.012452	4.5	16.8
Alt.	feet	.000010	.000150	.002407	15.0	16.0
V east	mfps	.001244	.001390	.011036	1.1	8.0
V north	mfps	.000062	.000860	.013759	13.9	16.0
V up	mfps	.000410	.004324	.067733	10.5	15.7
*Roll	µ deg.	.035517	.036532	.082230		
Pitch	µ deg.	.493597	.498660	.674350		
Heading	µ deg.	.000033	.000118	.001736		

*Attitude at 128 Hz for all of #7, #8, #9
(278 µdeg. = 1 sec)
* { 2.74 µdeg. = 1 foot (Lat.)
{ 3.88 µdeg. = 1 foot (Long. at 45° Lat.)

Table 4

Comparison of Time RMS Errors at End of 8 Sec., 8 Hz LV Runs vs. Incremental and Angular Quantization

Errors Type	Units	Magnitude			Ratio	
		Fine Seq. #12	Moderate Seq. #11	Coarse Seq. #10	#11/#12	#10/#11
Long.	μ deg.	.00794	.02756	.1581	3.47	5.74
Lat.	μ deg.	.01749	.05387	.2218	3.08	4.12
Alt.	feet	.00561	.01950	.07443	3.48	3.82
V east	mfps	1.668	4.812	19.52	2.88	4.06
V north	mfps	1.436	6.175	22.56	4.30	3.65
V up	mfps	1.399	5.750	21.71	4.11	3.78
Roll	μ deg.	192.9	972.3	2736.	5.04	2.81
Pitch	μ deg.	607.3	2540	9989.	4.18	3.93
Heading	μ deg.	762.8	2566	8068.	3.36	3.14
Quant. Vel	mfps	2.50	10.0	40.0		
Quant. Ang.	sec μ deg.	4.95 1375	19.8 5500	79.2 22002.		
Expected V	mfps	1.443	5.774	23.09		
Expected θ	μ deg.	561 to 794	2246 to 3175	8982 to 12703		

Table 5

Comparison of Time RMS Errors
at End of 8 Sec., 8 Hz LV Runs
- Effects of Quantization & All Else
vs. Quantization Only

Error Type	Units	Magnitude		Ratio
		Seq. #10	Seq. #5	#5/#10
Long.	μ deg.	.1582	8.827	5.58
Lat.	μ deg	.2218	16.46	74.3
Alt.	feet	.07443	.6384	8.58
V east	mfps	19.52	19.13	0.98
V north	mfps	22.56	21.89	0.97
V up	mfps	21.71	21.47	1.00
Roll	μ deg.	2,736.	4,034.	1.48
Pitch	μ deg.	9,989.	10,525.	1.05
Heading	μ deg.	8,068.	16,063.	1.99

Table 6

Comparison of Time RMS Errors at End of 8 Sec., 8 Hz, LV Runs

Effects of Word Length Full Precision vs. 8-Bit Exponent, 24 Bit Mantissa

Errors Type	Units	Magnitude Full Precision Seq. #2*	Magnitude 8 Bit & 24 Bits Seq. #5	Ratio #5/#2
*Long.	μ deg.	11.080	8.827	0.80
Lat.	μ deg.	.8187	16.46	20.1
Alt.	feet	.6384	.6384	1.00
V east	mfps	21.47	19.13	0.89
V north	mfps	19.18	21.89	1.14
V up	mfps	21.89	21.47	0.98
Roll	μ deg.	4034.	4034.	1.00
Pitch	μ deg.	10525.	10525.	1.00
Heading	μ deg.	16062.	16063	1.00

*Both use baseline software and coarse quantization.

*Longitude error at 1 second is 11.6 μ deg.

IV. Long Term Simulations

Background

At the AFAL-CSDL meeting on 8th and 9th of Jun it was agreed that the mission to be used for the long runs should be a three hour F-4 combat interdiction mission for which AFAL had the PROFGEN inputs on file. The file name was supplied to CSDL.

The characteristics of the IMU and navigation computer were defined by AFAL as follows:

1) IMU - local wander azimuth
   - 0.040 fps per pulse incremental velocity quantization
   - 14-bit gimbal angle encoders
   - 0.40 arc seconds per pulse gyro torquer quantization

2) Navigation Computer
   - floating point (8 bit exponent and 24 bit mantissa)
   - 0.25 second navigation (and attitude) iteration rate.

PROFGEN was to be run, using the specified mission, at 16 Hz, and the version which computes the integrals of specific force.

Two runs were to be performed: one using the "baseline" software and the other the "upgraded" or "full" software. Error outputs would be printed every 60 seconds (including the rms errors). Calcomp plots would be made including the difference between the instantaneous errors.

Results would be provided by an informal memo type report (later changed to an addendum to the Final Report).

Early Results and Interpretation

First attempted PROFGEN run aborted after 800 seconds of simulated time. It was also noted that file specified by AFAL started not at the beginning of the mission, but at the start of the dynamic phase and included evasive maneuvers, attack, evasive maneuvers and climb out.

Two VUMSIM runs were performed using the "baseline" and the "upgraded" software (referred to as sequence numbers 16 and 17 respectively). The instantaneous and time rms position and velocity errors were plotted at 60 second intervals from the Hazeltine outputs and are shown in plots 26 through 37. A full set of 30 Calcomp plots for the "baseline" software run (sequence #16) are included as plots 38 through 67.

As anticipated, the "upgraded" software case provided smaller position errors than the "baseline" case.

A rough order of magnitude estimate of the relative sizes of the errors is provided by scaling of the error plots (see Table 7) while a more precise estimate is given by the ratio of the time rms errors (see Table 8). Attitude errors were almost identical in either case and reflected the expected values due to encoder quantization.

The most significant result of these runs was the growth rate of the horizontal position errors in the "baseline" case. The rate error was on the order of 0.10 knots, or compatible with the computational portion of the error budget for a moderate accuracy aircraft inertial navigation system.

TABLE 7

ROM ESTIMATE
of
ERROR RATIOS
from
PLOT SCALING

(Baseline/Upgraded)

Error Name	Plot Scale Ratio
Latitude	2.5
Longitude	2.5
Attitude	50.0
North Velocity	1.0
East Velocity	1.0
Vertical Velocity	20.0

TABLE 8

UPGRADED/BASELINE SOFTWARE

Ratio of RMS Errors at 660 Sec

Error	Units	Baseline	Upgraded	B/U
Longitude	μ degrees	241	53	4.55
Latitutde	μ degrees	215	62	3.47
Altitude	feet	11.8	0.22	53.60
East Velocity	mfeet/sec	42	55	0.765
North Velocity	mfeet/sec	30	26	1.15
Up Velocity	mfeet/sec	370	15	24.9

FIRST LONGER RUNS - RESULTS AND INTERPRETATION

A second PROFGEN through 6300 + seconds was performed (the roll rate used in horizontal turns was reduced from 450 to 250 degrees per second.)

"Baseline" and "full" software VUMSIM runs were performed (through 4800 seconds). The resulting RMS errors at 4500 seconds are summarized in Table 9. Calcomp plots of the difference of the instantaneous errors between the two runs are shown in plots 68 through 77.

In general, the navigation errors from the "full" software case were much smaller than the corresponding errors from the "baseline" case. The anomaly occurred in latitude with the "full" software run; here the rms latitude error was about four times larger than in the "baseline" case.

The appearance of this anomaly initiated a month long investigation to localize and identify the source of the error or errors and fix same.

Table 9
RMS Errors (Seq. #16, 17) at 4500 Sec.

Error	Units	BSW	FSW	Ratio B/F
Lat.	μ deg.	390	1525	0.26
Long.	μ deg.	1127	360	3.13
Alpha	μ deg.	539	262	2.06
Alt	feet	4.55	0.09	50.5
V_x (up)	milli fps	144	12.2	11.8
V_y (east)	milli fps	173	44.9	3.86
V_z (north)	milli fps	131	110	1.19
Roll	milli deg.	5.7	5.9	0.97
Pitch	milli deg.	6.1	6.1	1.00
Yaw	milli deg.	12.3	12.9	0.95

Latitude Anomaly Investigation

Symptoms

Examination of the north velocity and latitude errors indicated that the position error was not the integral of the velocity error in the "full" software run (sequence #17).

Initial Hypotheses

Since we were dealing with errors at this time it was not clear whether the errors were due to some inadequacy in the variable precision simulator program (VUMSIM) or in the profile, i.e., inconsistencies in the position, velocity, and integrals of specific force output by PROFGEN.

Special Tests and Results

Numerous special simulation runs over part or all of the trajectory used in sequences #16 and #17, were performed to isolate the problem. Most of these runs employed the version of the simulator without variable precision, (NUMSIM) with no quantization and with 16 Hz navigation and attitude computations.

All these runs display relatively small systematic position and velocity errors, the position errors were the integrals of the velocity errors and the familiar forms of the Schuler oscillations were apparent, e.g., the velocity errors were of the form $A \sin\omega_s t$ then the corresponding position error was of the form $(A/\omega_s)(1 - \cos\omega_s t)$. The magnitude of A corresponded to an accelerometer bias error or "tilt" error ranging from a fraction of a micro-g or microradian up to 2 or 3 micro-g's or microradians.

AFAL acknowledged the existence of a sign error in one of the horizontal components of "g" at altitude, which would account for the kind and magnitude of errors mentioned in the preceding paragraph.

Simulation runs switched to the variable precision form (VUMSIM) where the 48-bit case corresponded exactly to NUMSIM. The 32-bit VUMSIM results departed microscopically from the 48-bit case. When the corresponding 24-bit case was run, the anomaly obligingly reappeared.

Further testing and analysis indicated that 24-bits were too few for position integration. This situation was further aggravated by orthonomalization which turned the direction cosine matrix errors into rotational errors (which latter appeared as drift rate errors on the order of 8×10^{-3} degrees per hour).

Fixes and New Results

Since 32 bits was good and 24 bits was bad, VUMSIM was modified to perform the direction cosine matrix update and orthonormalization using 8 bits more than was used in the remainder of the program. The DCM per se is stored with the added 8 bits.

Runs at 4 Hz with this fix did not display the large latitude errors characterizing the original anomaly (note that no quantization was included at this point)--see plots #78 and #79.

Next, the sign on the one component of "g" was changed in PROFGEN and the profile was regenerated. A 16 Hz NUMSIM run with the "full" software and no quantization revealed that the longitude error had about doubled compared with the "old" PROFGEN instead of vanishing (see plots #80 and #81).

After performing several 4 Hz runs with and without quantization but with extended precision in the DCM operations (see plots 82, 83, 84, 85, 86 and 87) with rather inconclusive results, the "gravity" equations for NUMSIM/VUMSIM were reexamined for the n^{th} time. The suspect level component of "g" was found to have been originally compatible with PROFGEN (both had the wrong sign initially) so this sign was also reversed and the appropriate 4 Hz, 24 bits (32 for DCM) VUMSIM runs with quantization were repeated with results not significantly different from those shown in plots 82, 83, 86 and 87.

This concluded the computer work performed to date.

PROFGEN Outputs Before and After Change in Sign of GY

Over the F-4 mission, changing the sign of GY in PROFGEN introduces change in east-west acceleration of about 2 micro-g's over most of the flight. Doubly integrated, over 5000 seconds, this would represent about 3000 microdegrees of longitude or about 800 feet. Applied to a Schuler loop, the peak position error (after half a Schuler period) would be about 1/10 of the above.

The actual difference in the PROFGEN longitude due to this change in acceleration, at 4800 seconds into the run, was 1.2 microdegrees or about 4 inches. This might lead one to conclude that the PROFGEN position (and velocity) are not quite compatible with its specific force (integrals).

Conclusions and Recommendations

1) Extended precision is required for the position integration - 24 bits is not adequate while 32 bits is more than adequate. Therefore, the DCM update should be performed using 32-bit fixed point arithmetic (corresponding to the present VUMSIM mechanization).

2) Similar extended precision would be useful in the velocity summing block. (This is not currently mechanized in VUMSIM).

3) The use of PROFGEN should be restricted to providing an incremental velocity profile. The reference data should be supplied by the "best" software NUMSIM run, i.e., full word length, no quantization, short computation cycle, etc. (The existing "differencing" program will accommodate this.)

4) Effects of quantization should be reevaluated after incorporation of extended precision velocity summing.

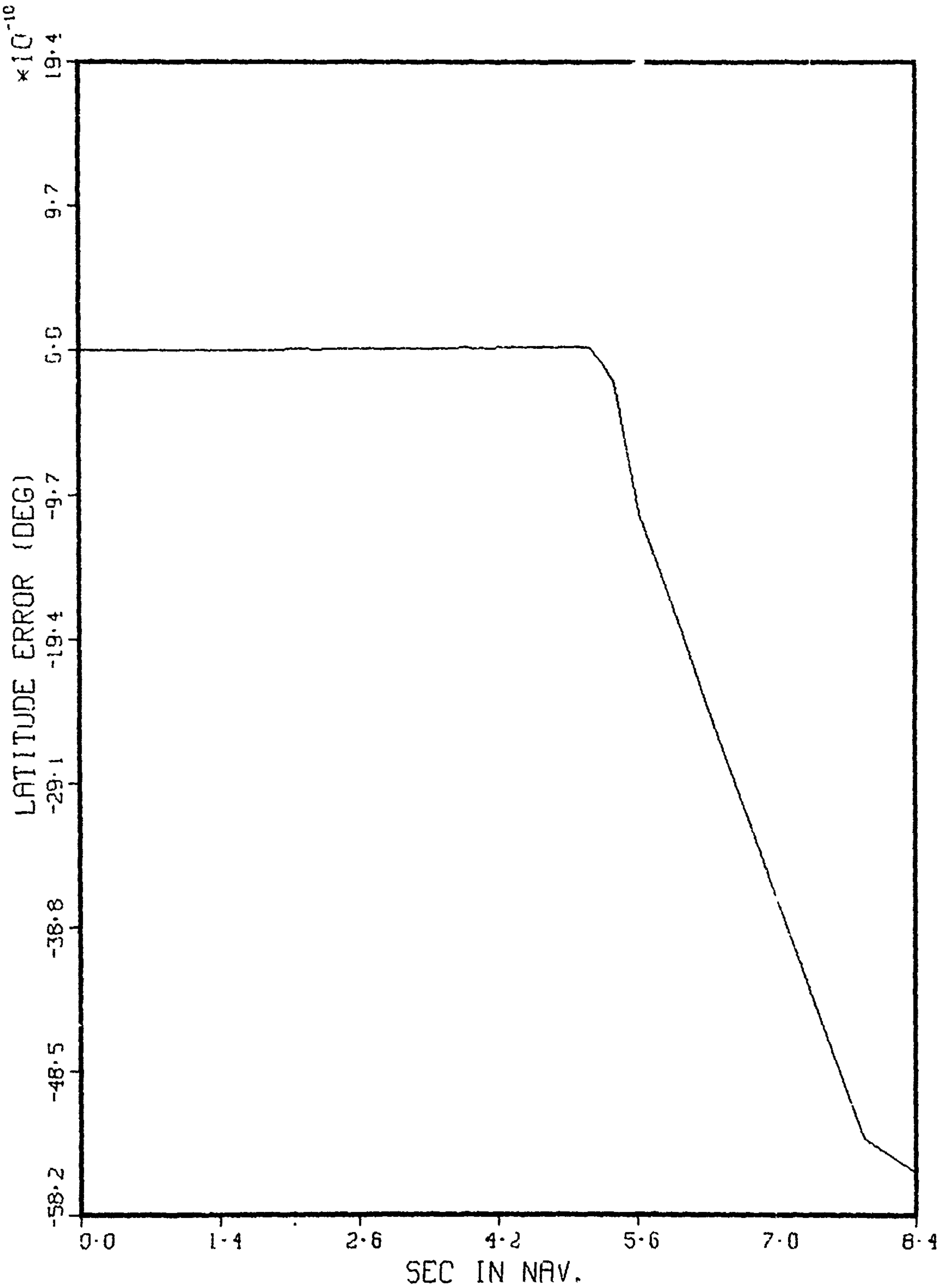
5) The effects of step inputs from PROFGEN becloud the propagation of computational errors during benign flight conditions.

6) The throughput capabilities of the existing remote terminal are not conducive to efficient analysis of the data available at the central processor.

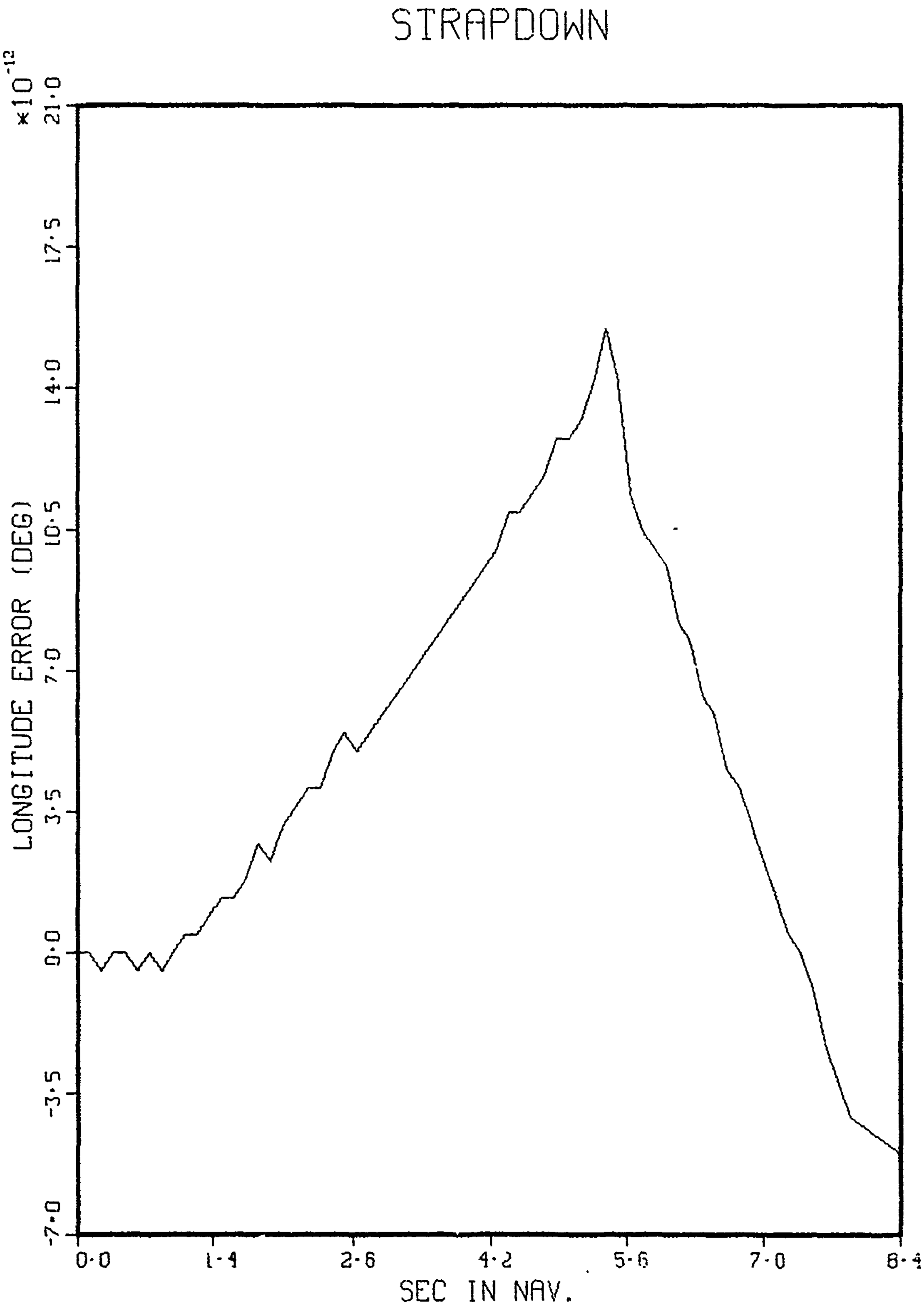
PLOTS 1 THROUGH 87

Plot #1

STRAPDOWN

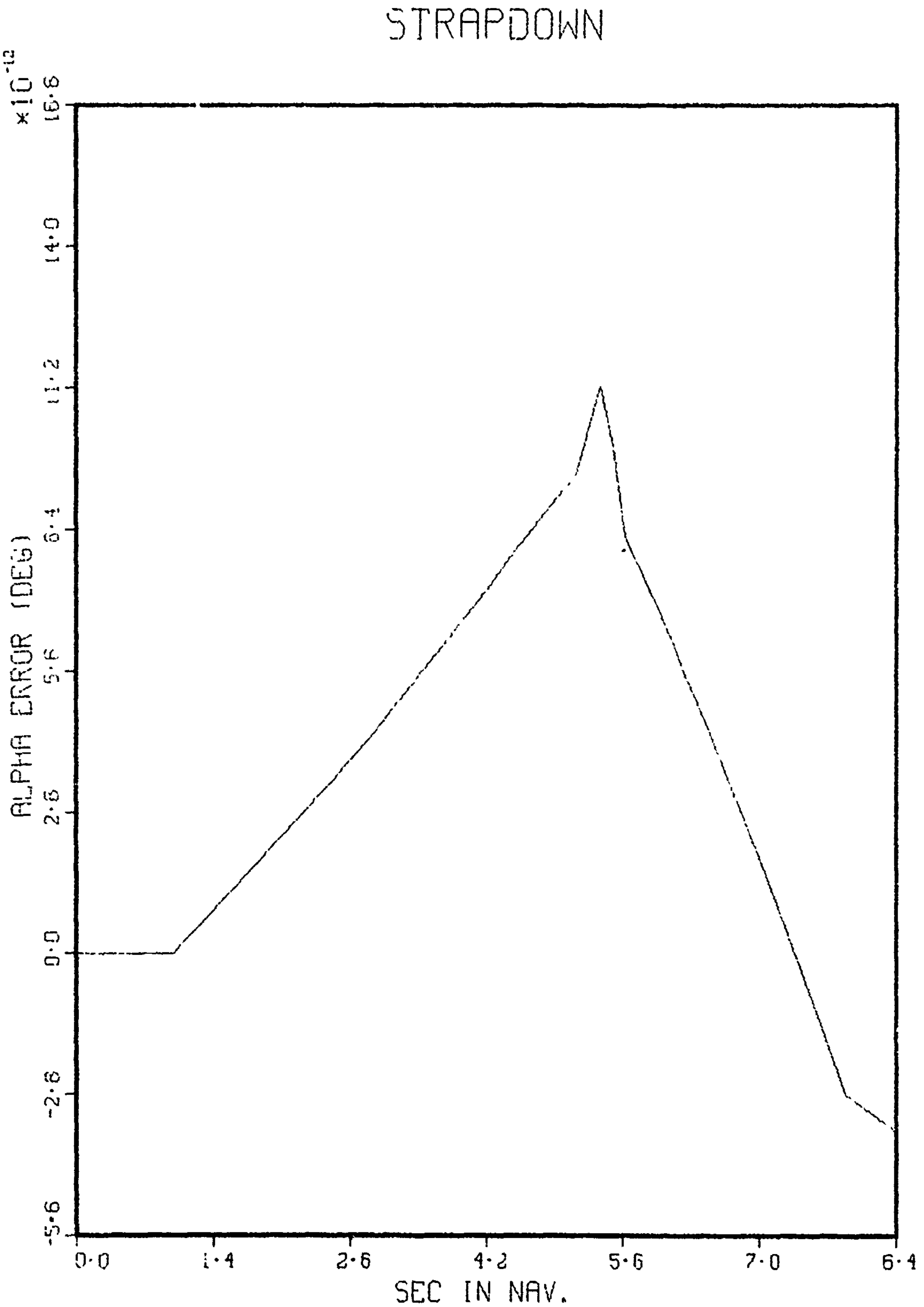


Plot #2

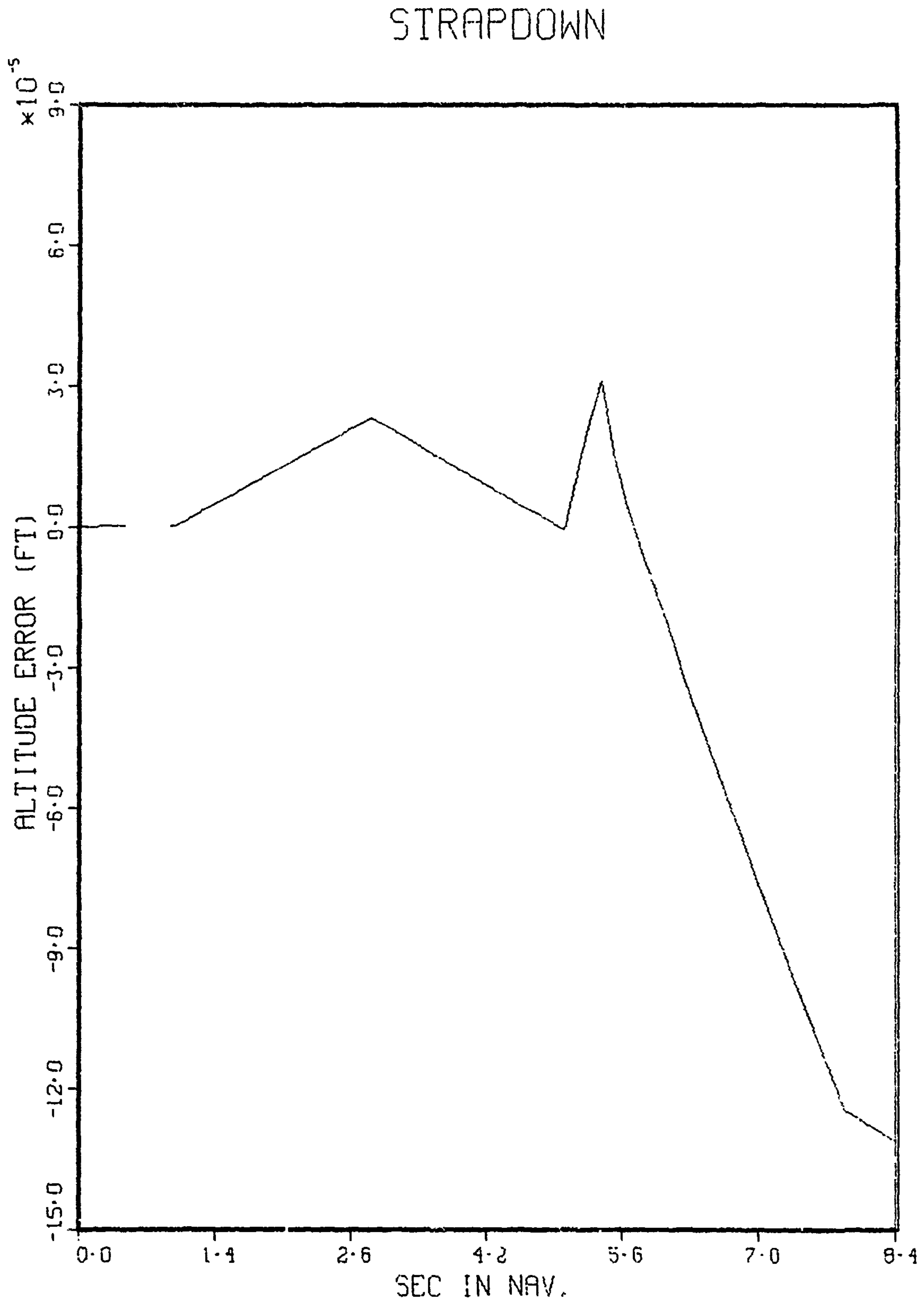


STRAPDOWN
*10^-12
21.0
17.5
14.0
10.5
7.0
3.5
0.0
-3.5
-7.0
LONGITUDE ERROR (DEG)
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.

Plot #3

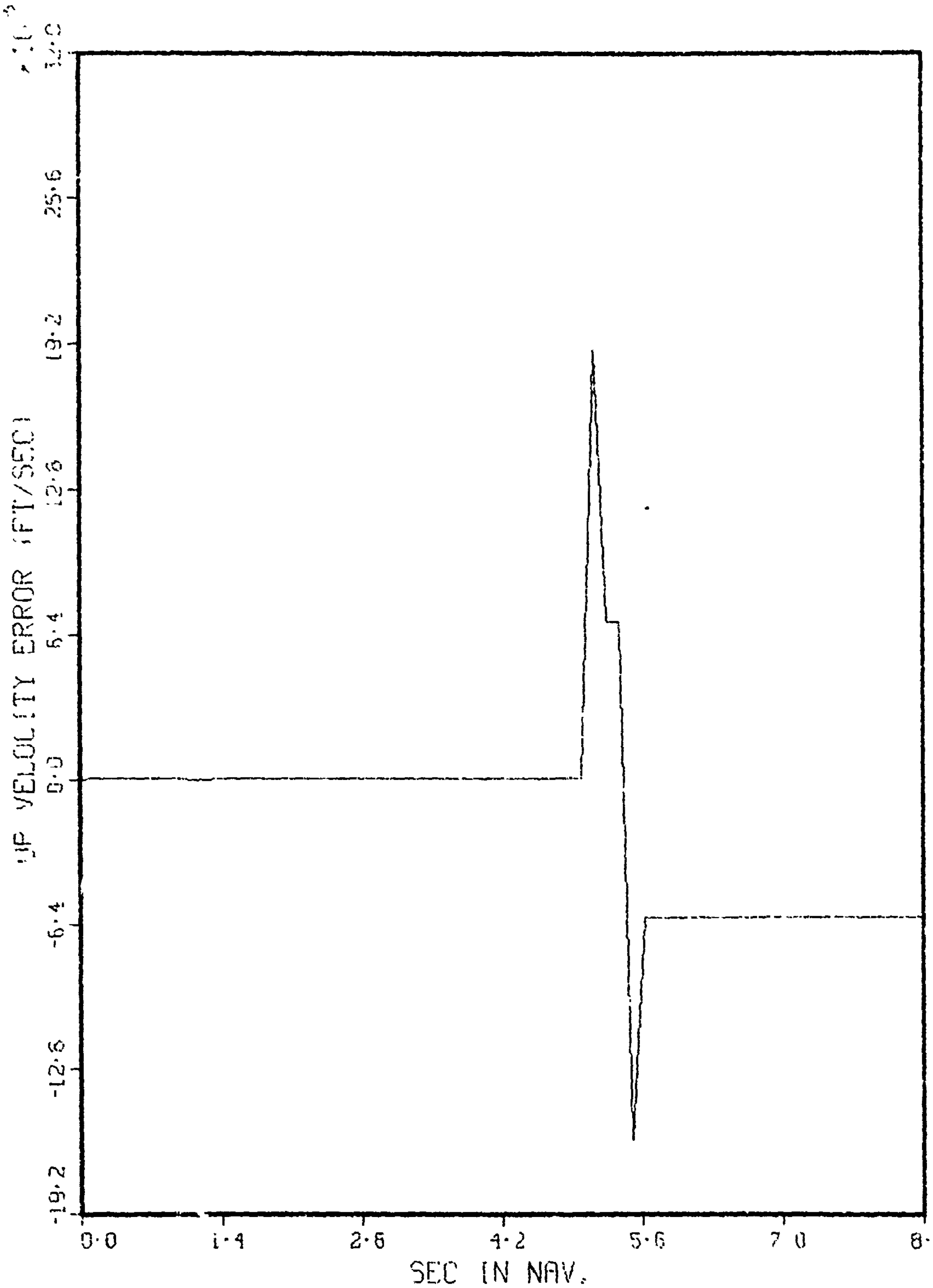

STRAPDOWN
×10^-12
16.6
14.0
11.2
8.4
5.6
2.8
0.0
-2.8
-5.6
ALPHA ERROR (DEG)
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.

Plot # 4

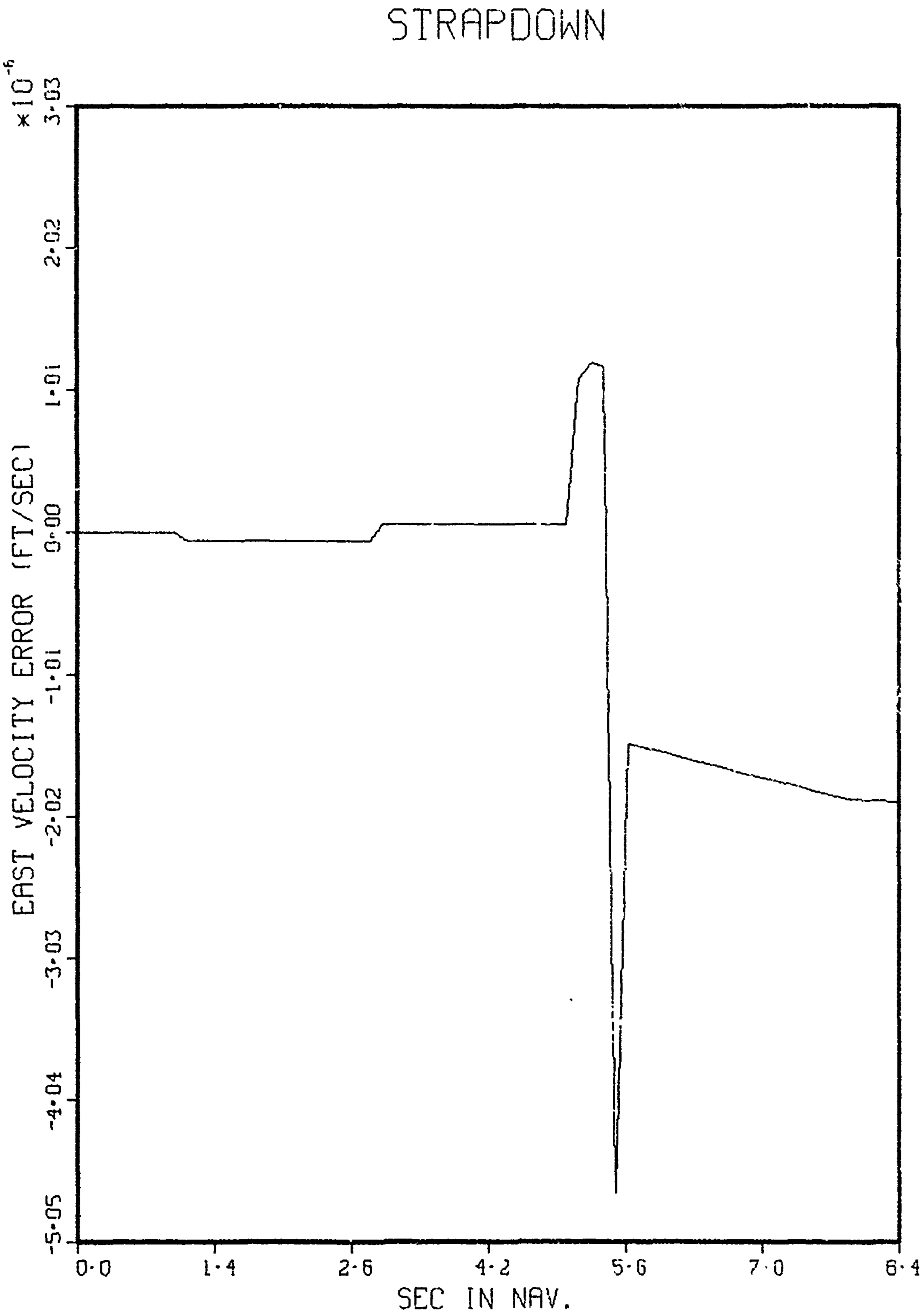

STRAPDOWN
×10^-5
ALTITUDE ERROR (FT)
9.0
6.0
3.0
0.0
-3.0
-6.0
-9.0
-12.0
-15.0
0.0
1.4
2.6
4.2
5.6
7.0
8.4
SEC IN NAV.

Plot #5

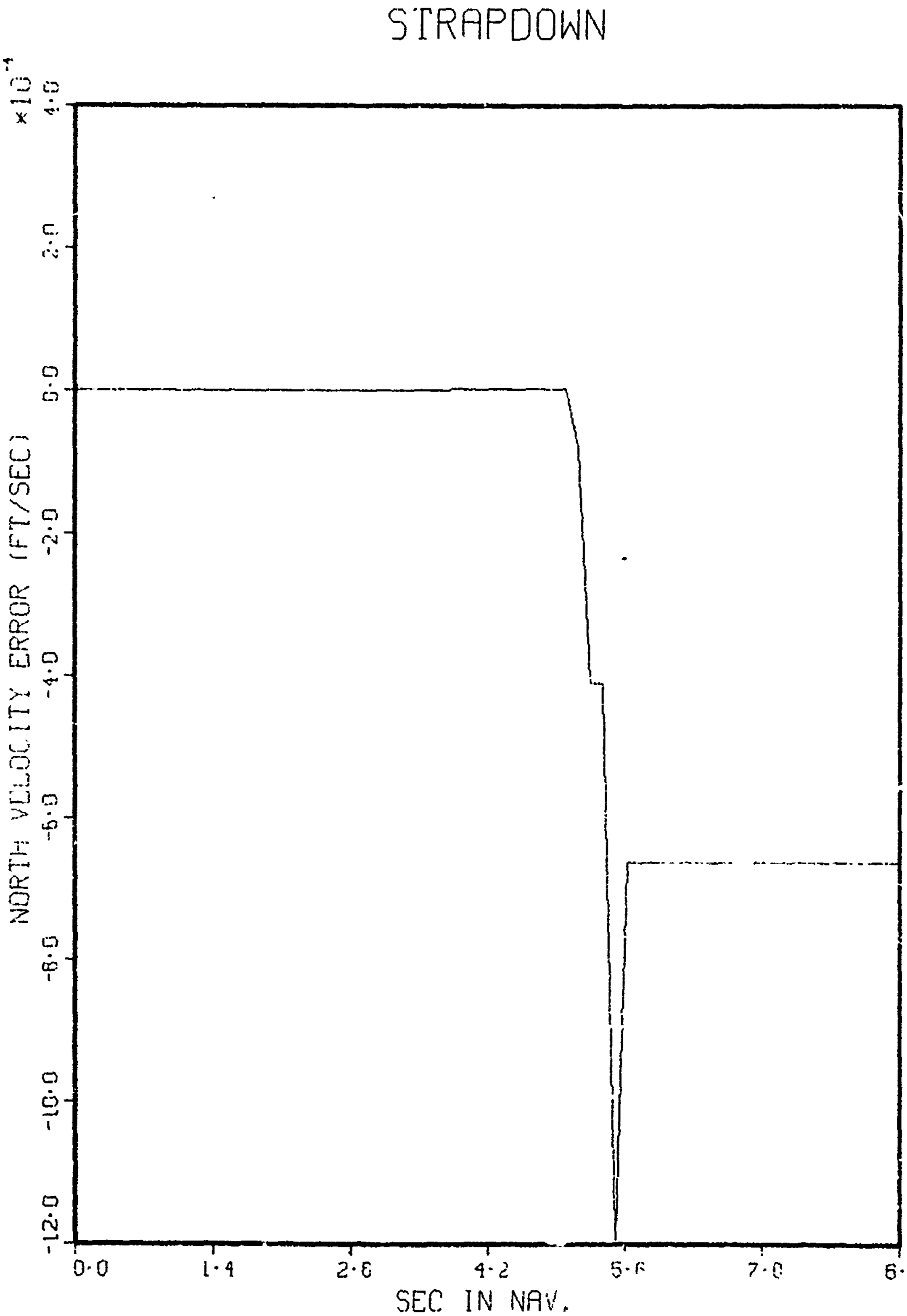
STRAPDOWN



Plot #6

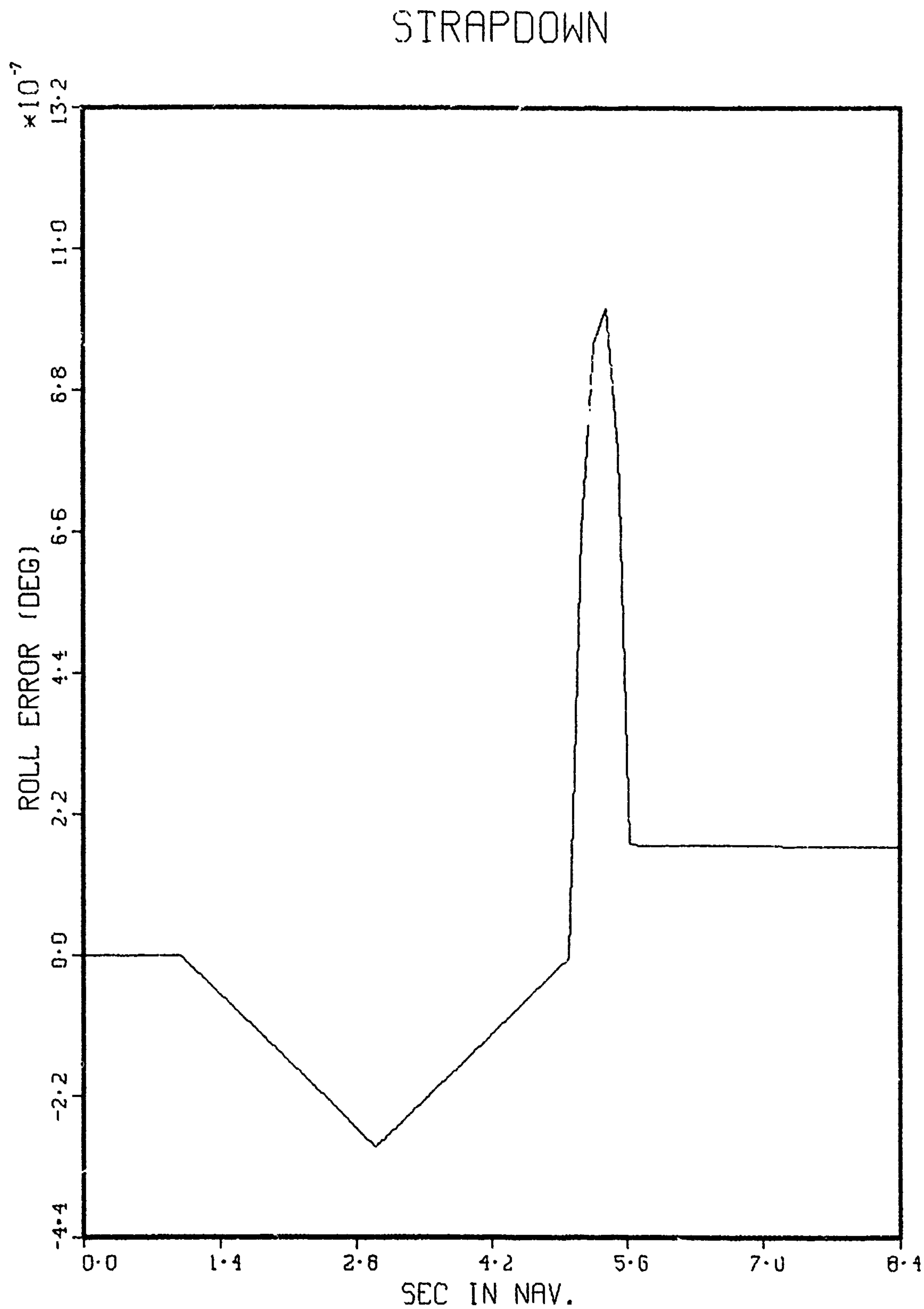

STRAPDOWN
$\times 10^{-6}$
EAST VELOCITY ERROR (FT/SEC)
3·03
2·02
1·01
0·00
-1·01
-2·02
-3·03
-4·04
-5·05
0·0
1·4
2·8
4·2
5·6
7·0
8·4
SEC IN NAV.

Plot #7



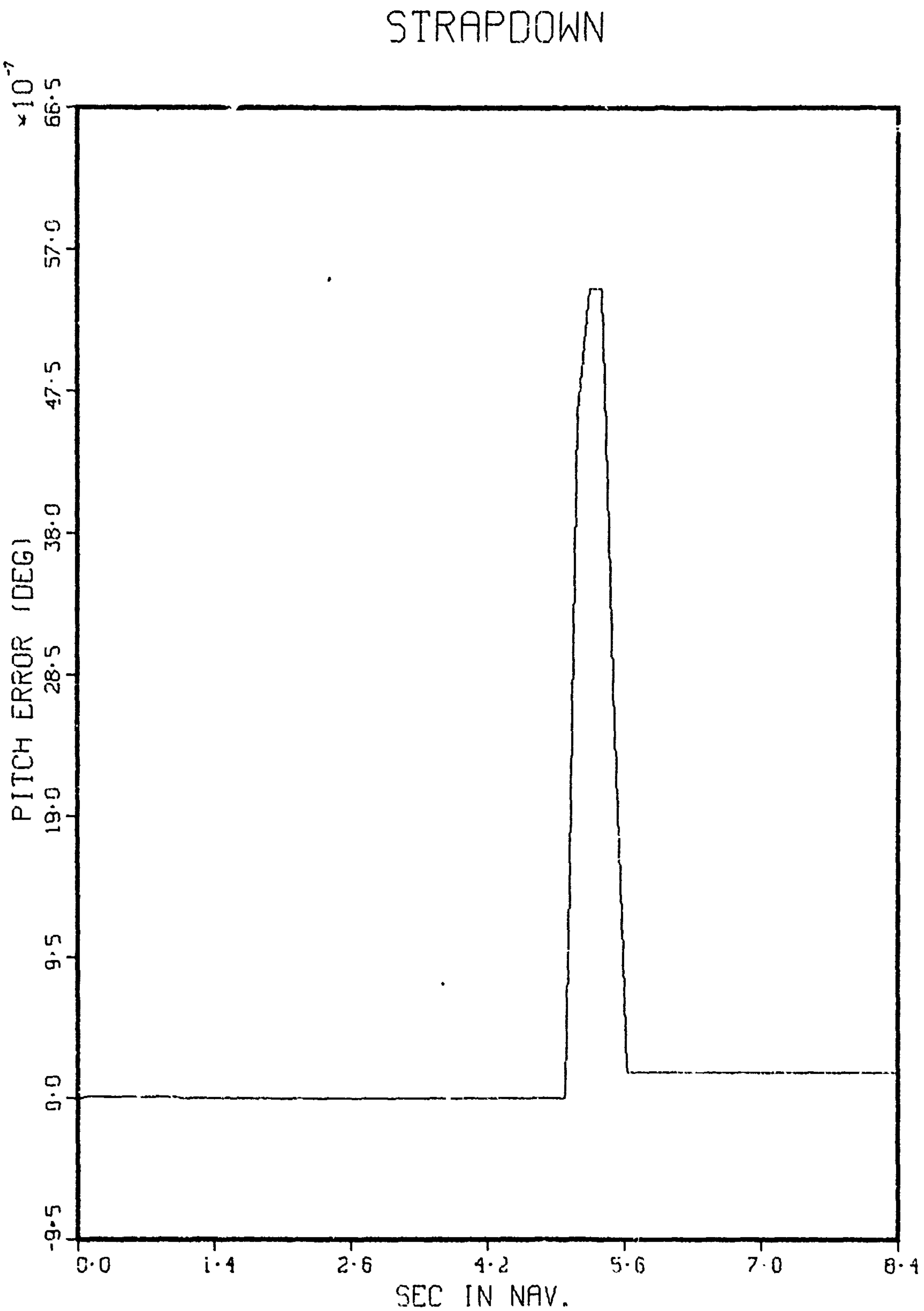
STRAPDOWN
×10⁻⁴
NORTH VELOCITY ERROR (FT/SEC)
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.

Plot #8



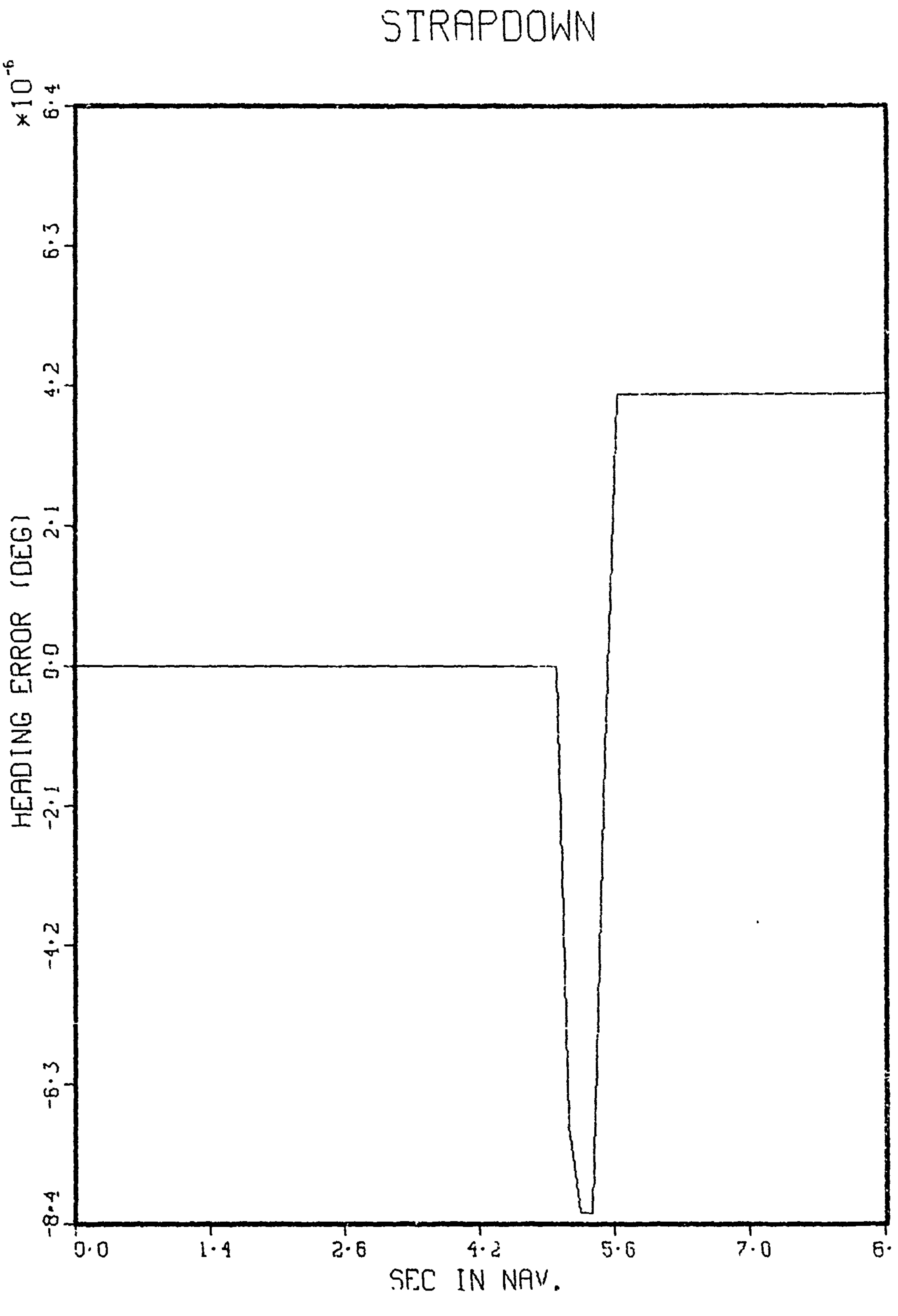
STRAPDOWN
ROLL ERROR (DEG)
*10^-7
13.2
11.0
8.8
6.6
4.4
2.2
0.0
-2.2
-4.4
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.

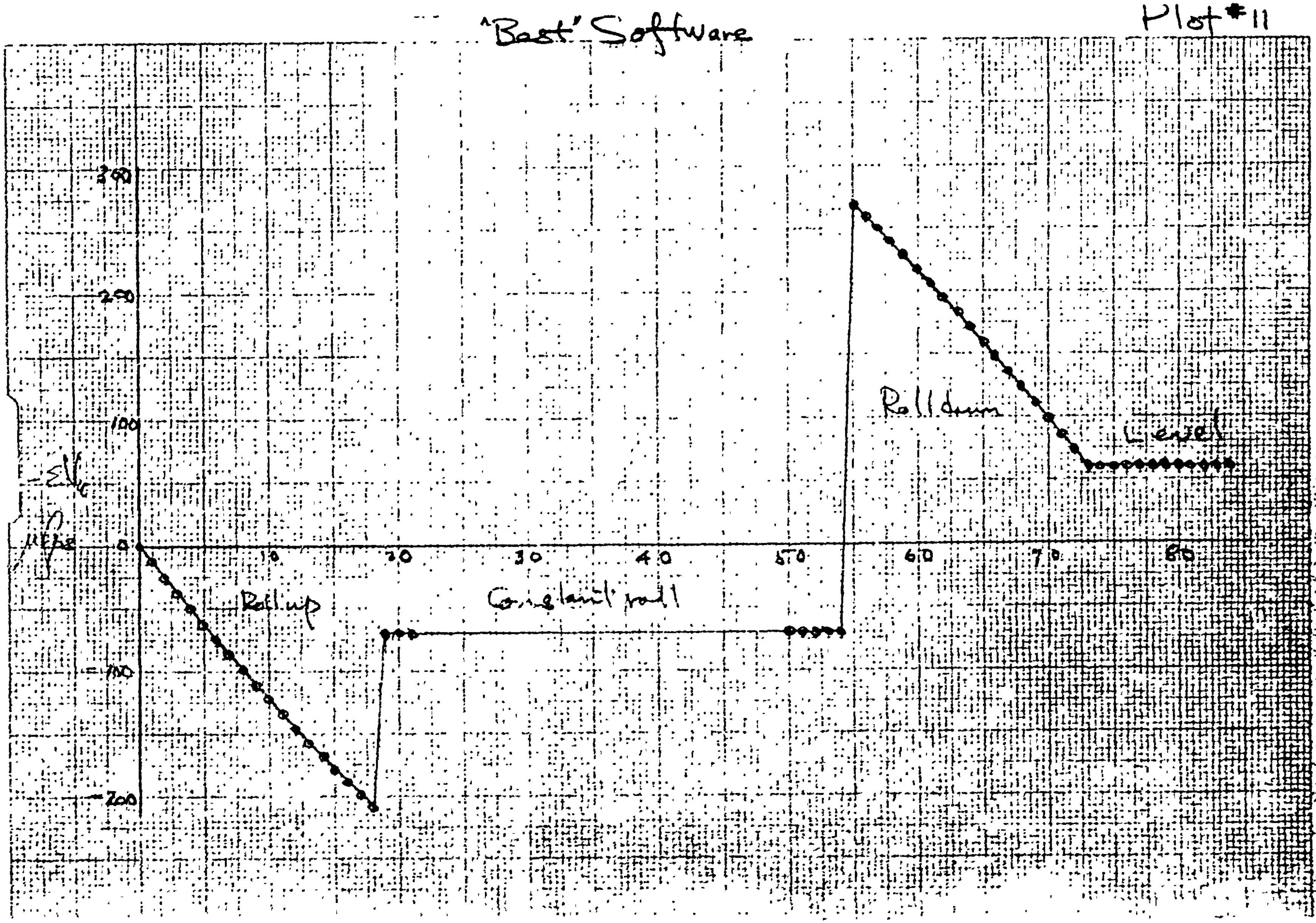
Plot #9



STRAPDOWN
$\times 10^{-7}$
PITCH ERROR (DEG)
66.5
57.0
47.5
38.0
28.5
19.0
9.5
0.0
-9.5
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.

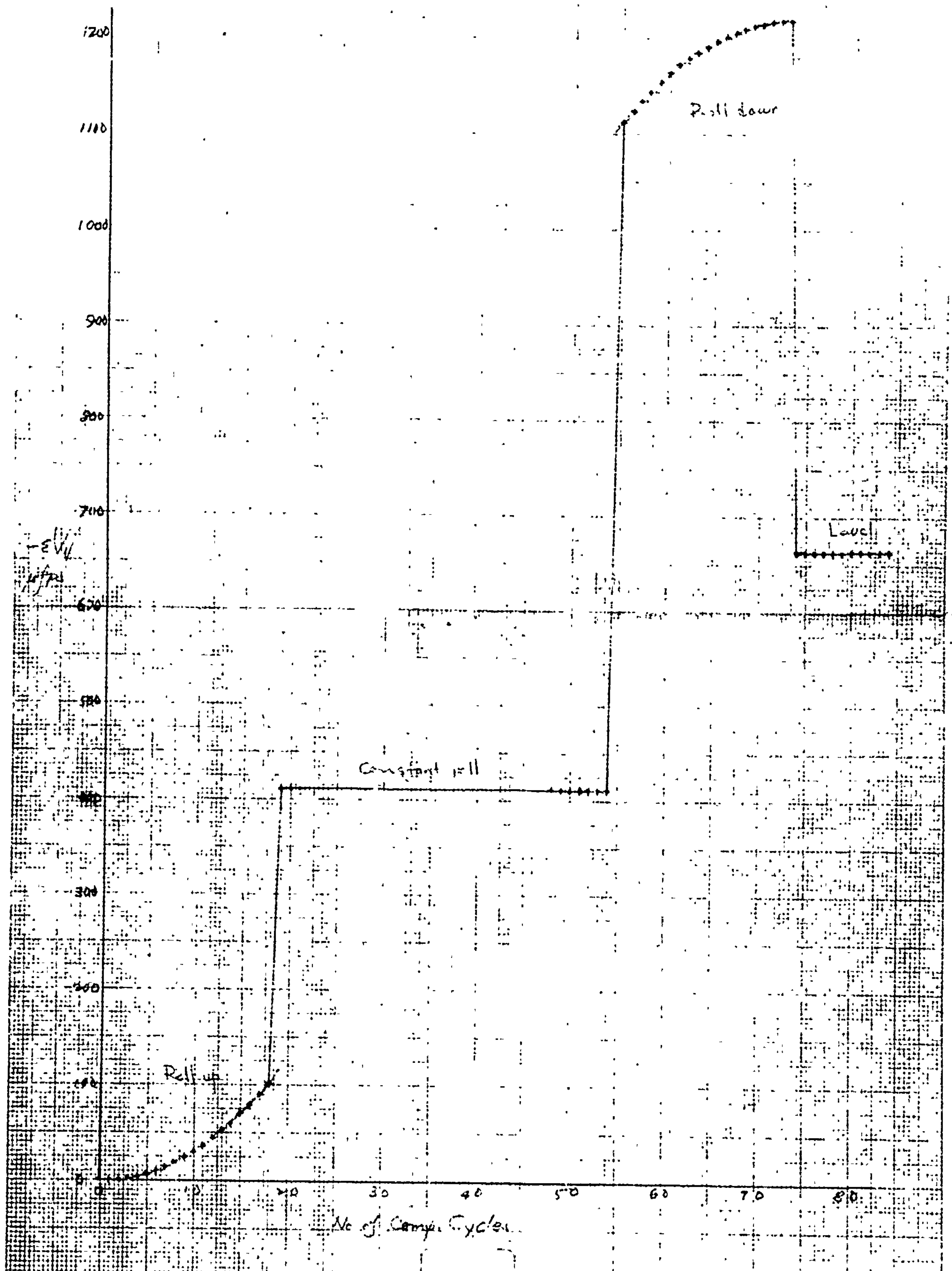
Plot #10


STRAPDOWN
$\times 10^{-6}$
HEADING ERROR (DEG)
8.4
6.3
4.2
2.1
0.0
-2.1
-4.2
-6.3
-8.4
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.


'Best' Software
Plot #11
300
200
100
0
-100
-200
10
20
30
40
50
60
70
80
Roll up
Constant roll
Roll down
Level

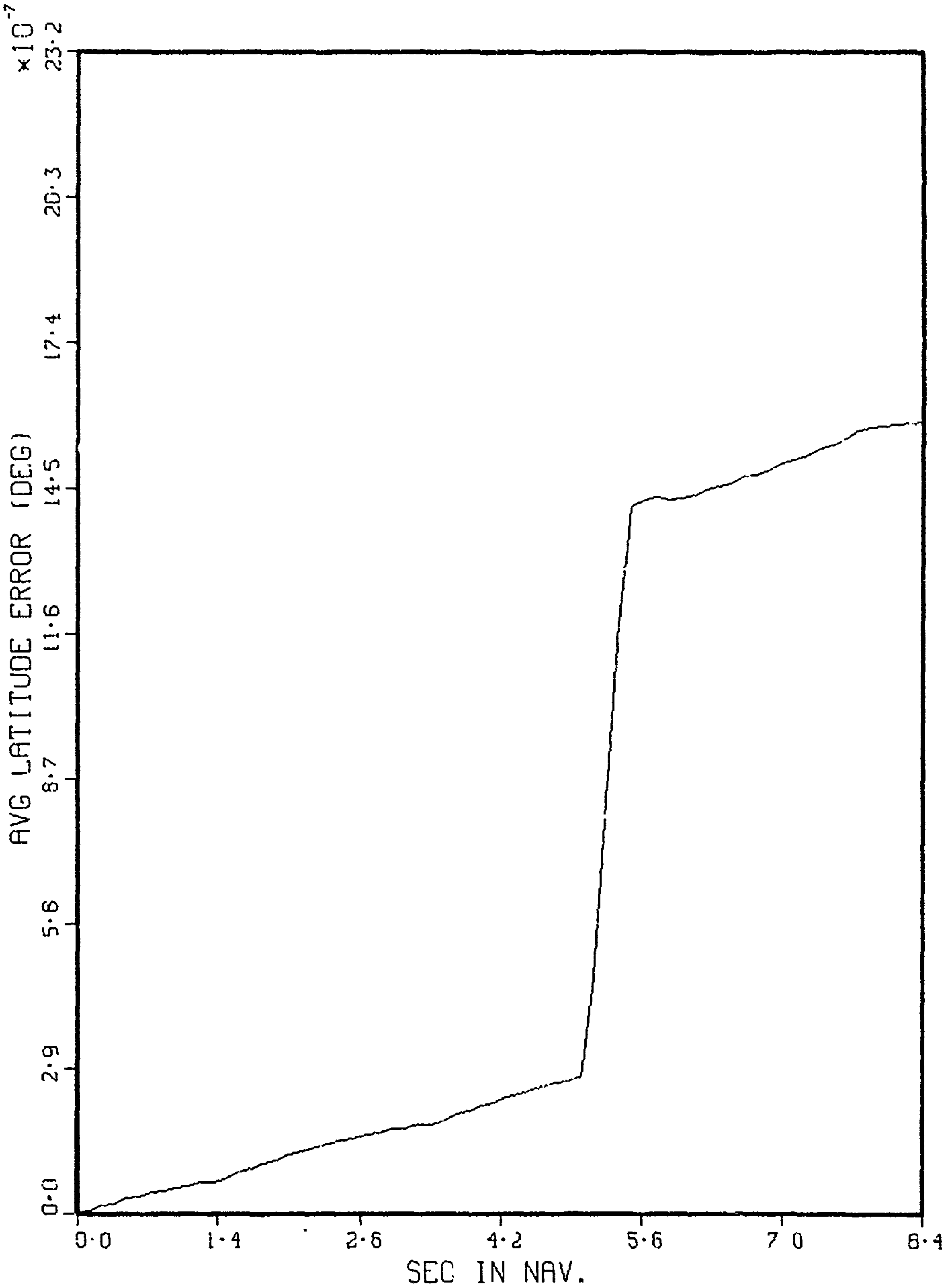
Plot #12

'Best' Software



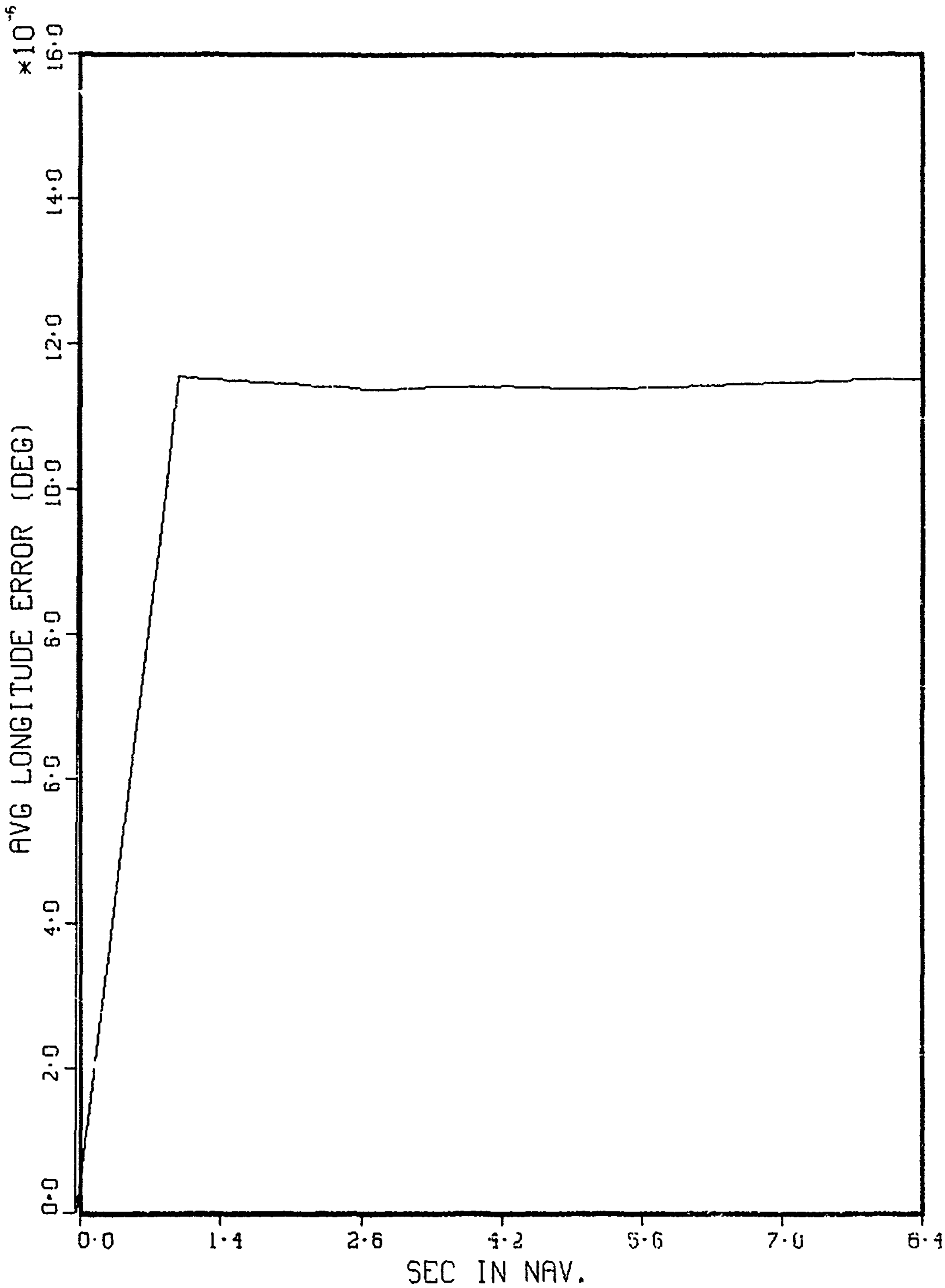
Plot #13

WORD LENGTH SEQ 1



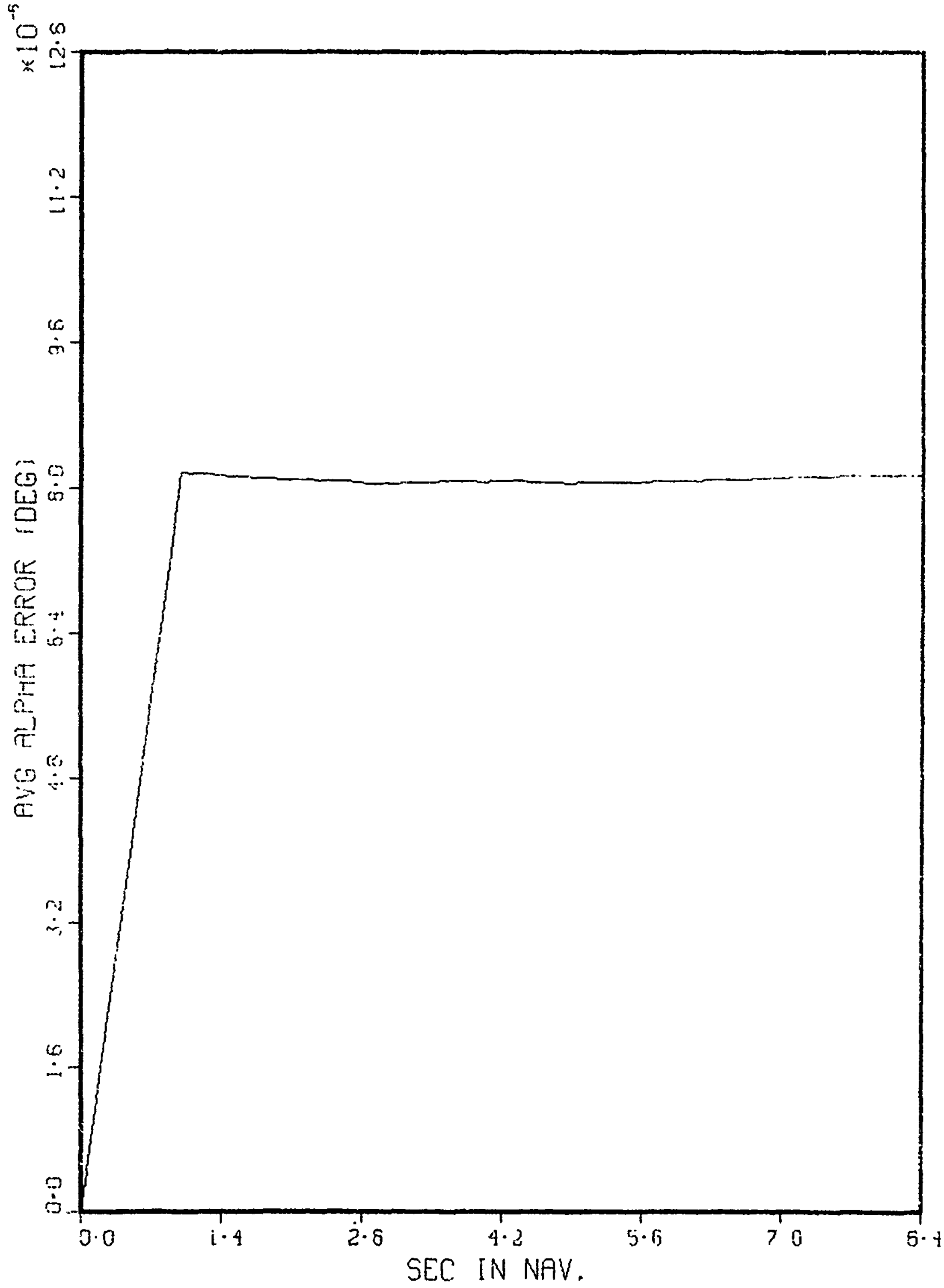
Plot #14

WORD LENGTH   SEQ 1



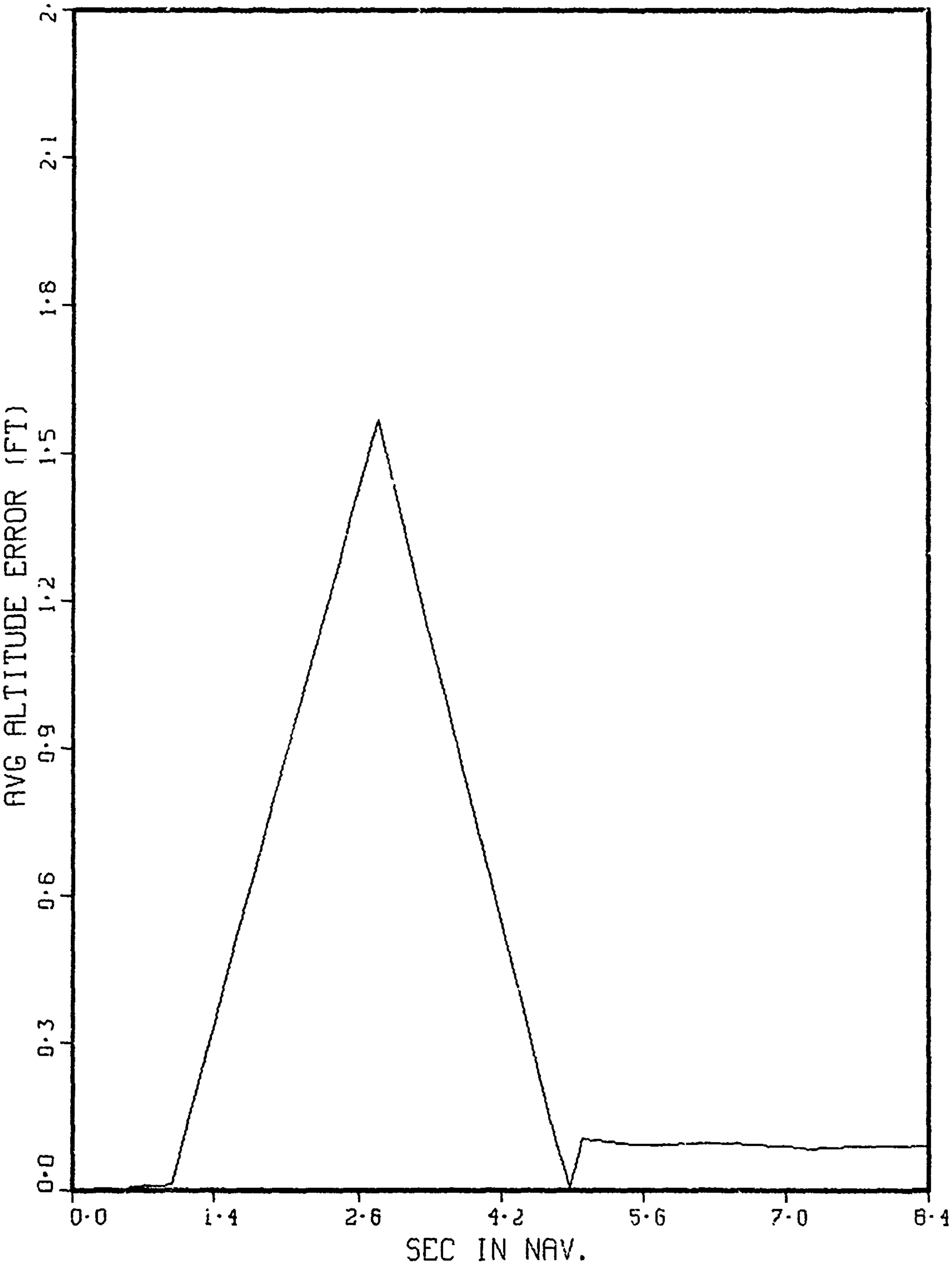
Plot #15

WORD LENGTH SEO 1



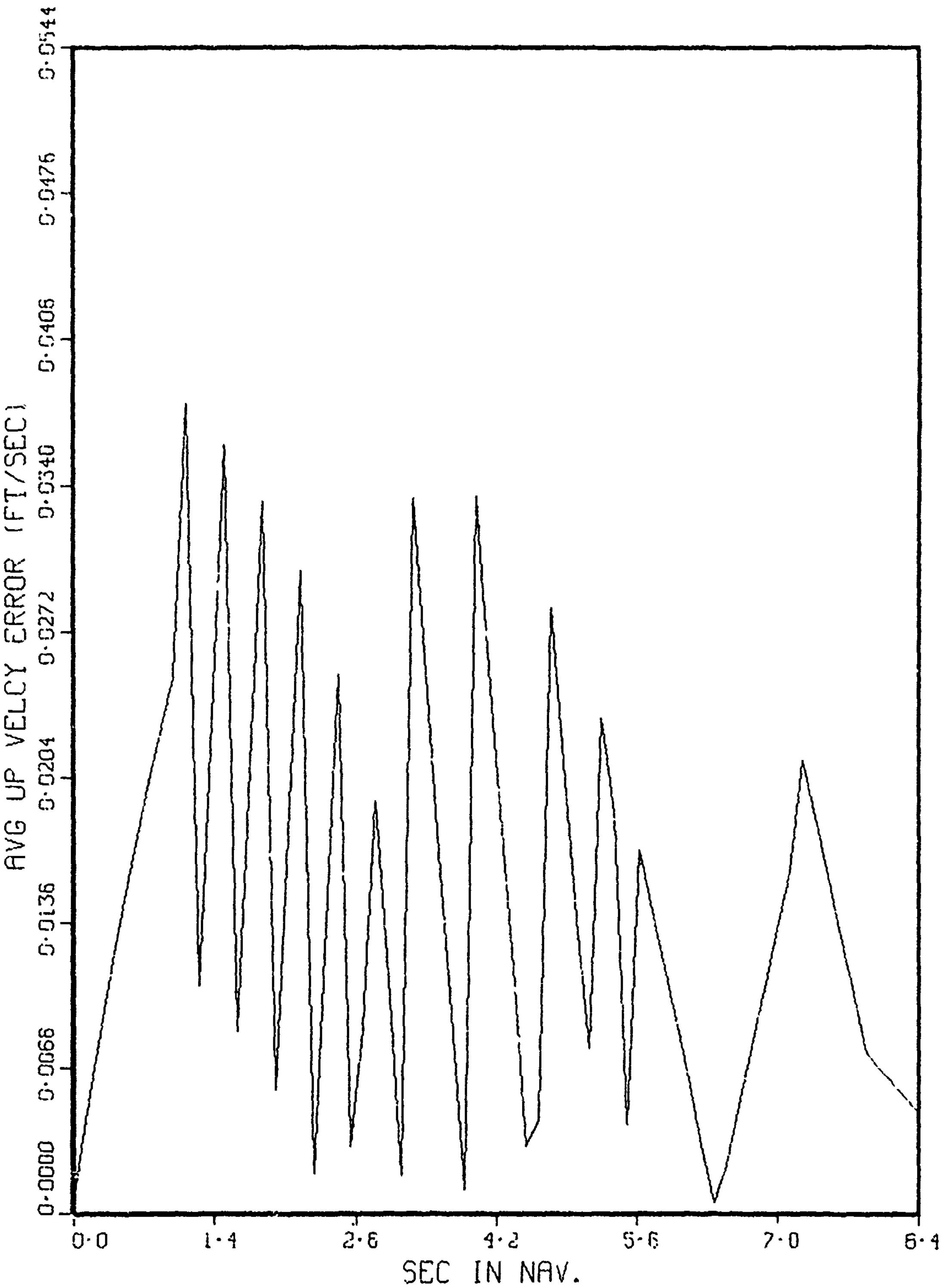
Plot #16

WORD LENGTH SEQ 1



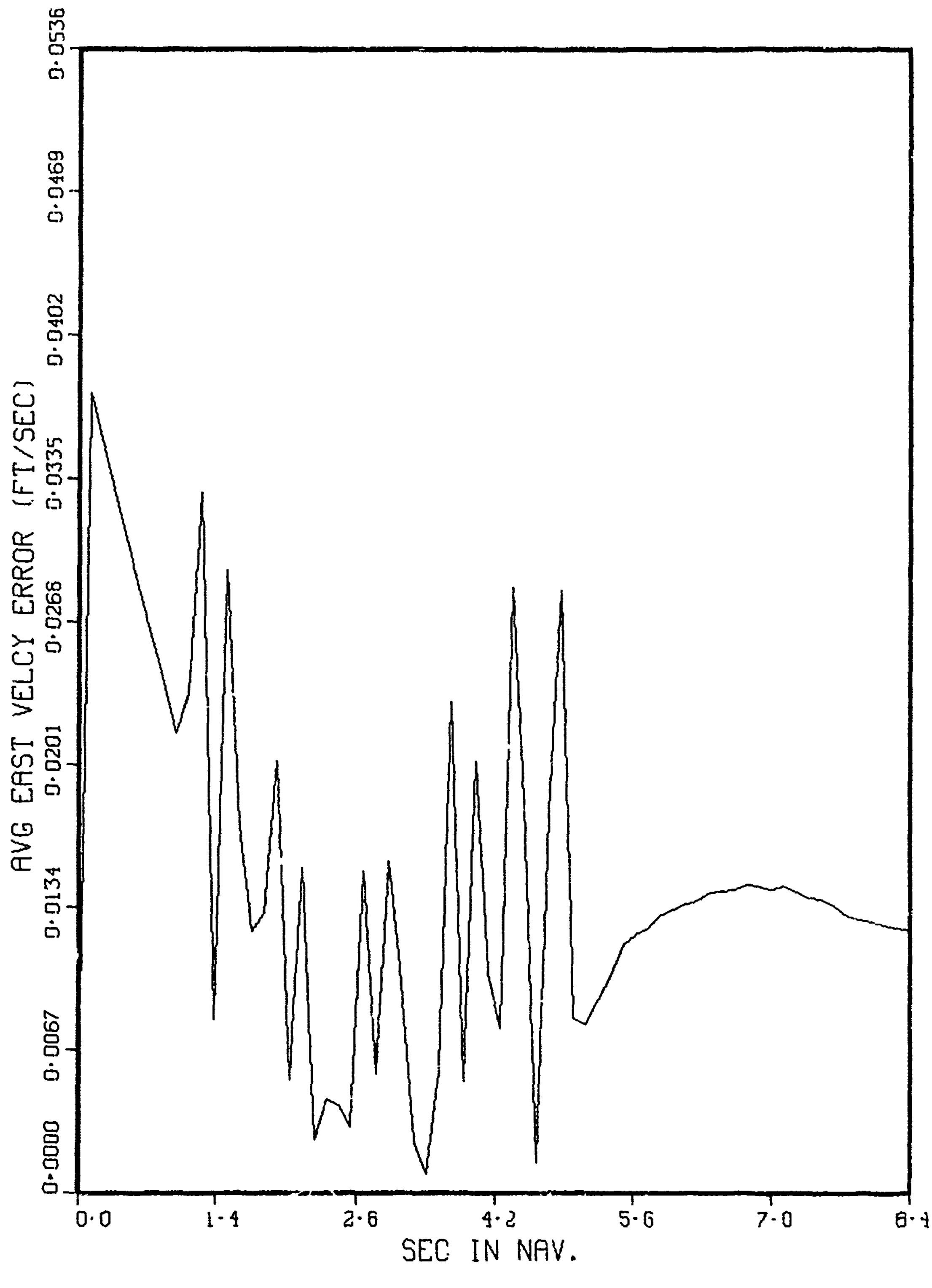
Plot #17

WORD LENGTH SEQ 1



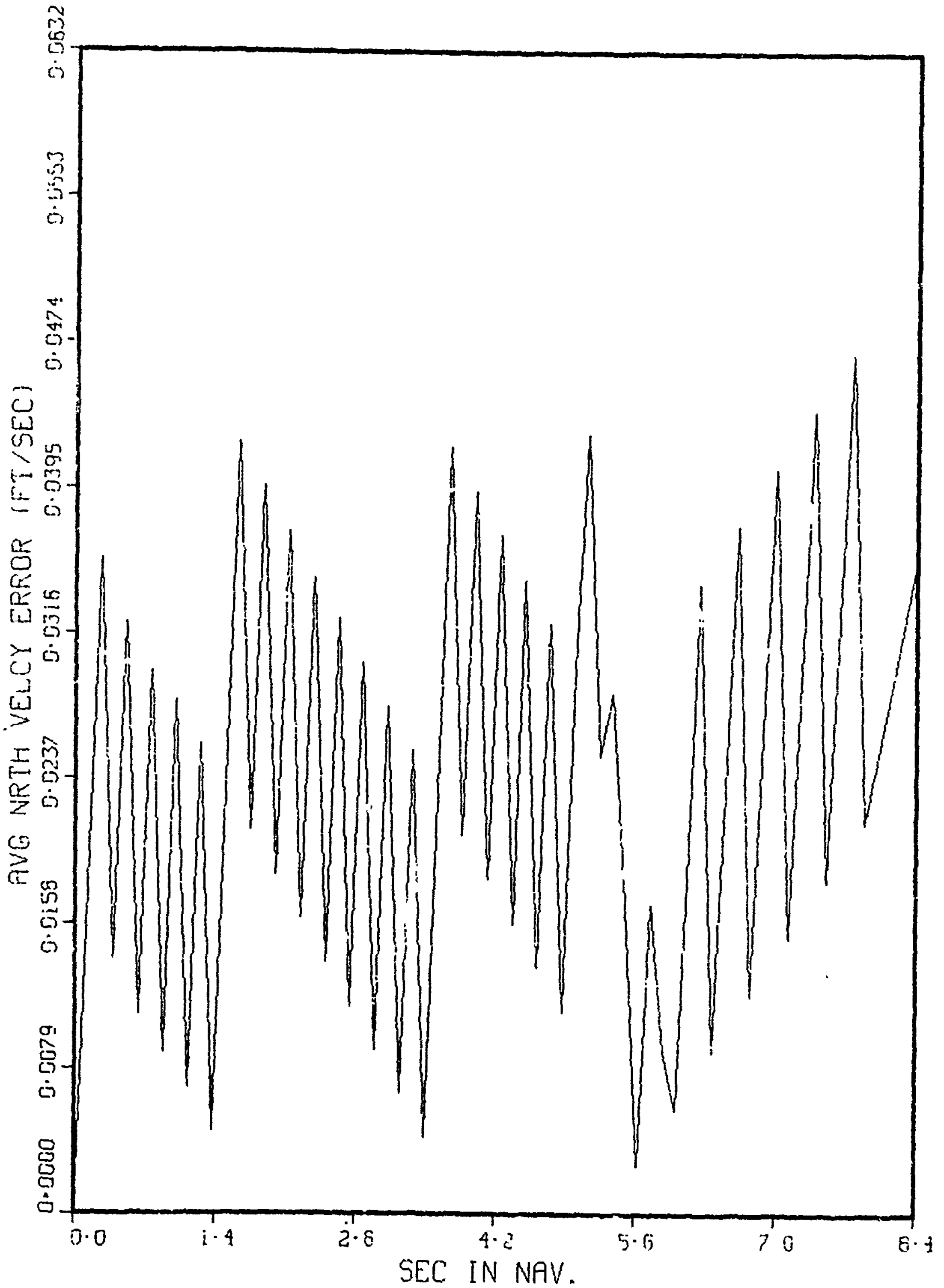
Plot #18

WORD LENGTH SEQ 1

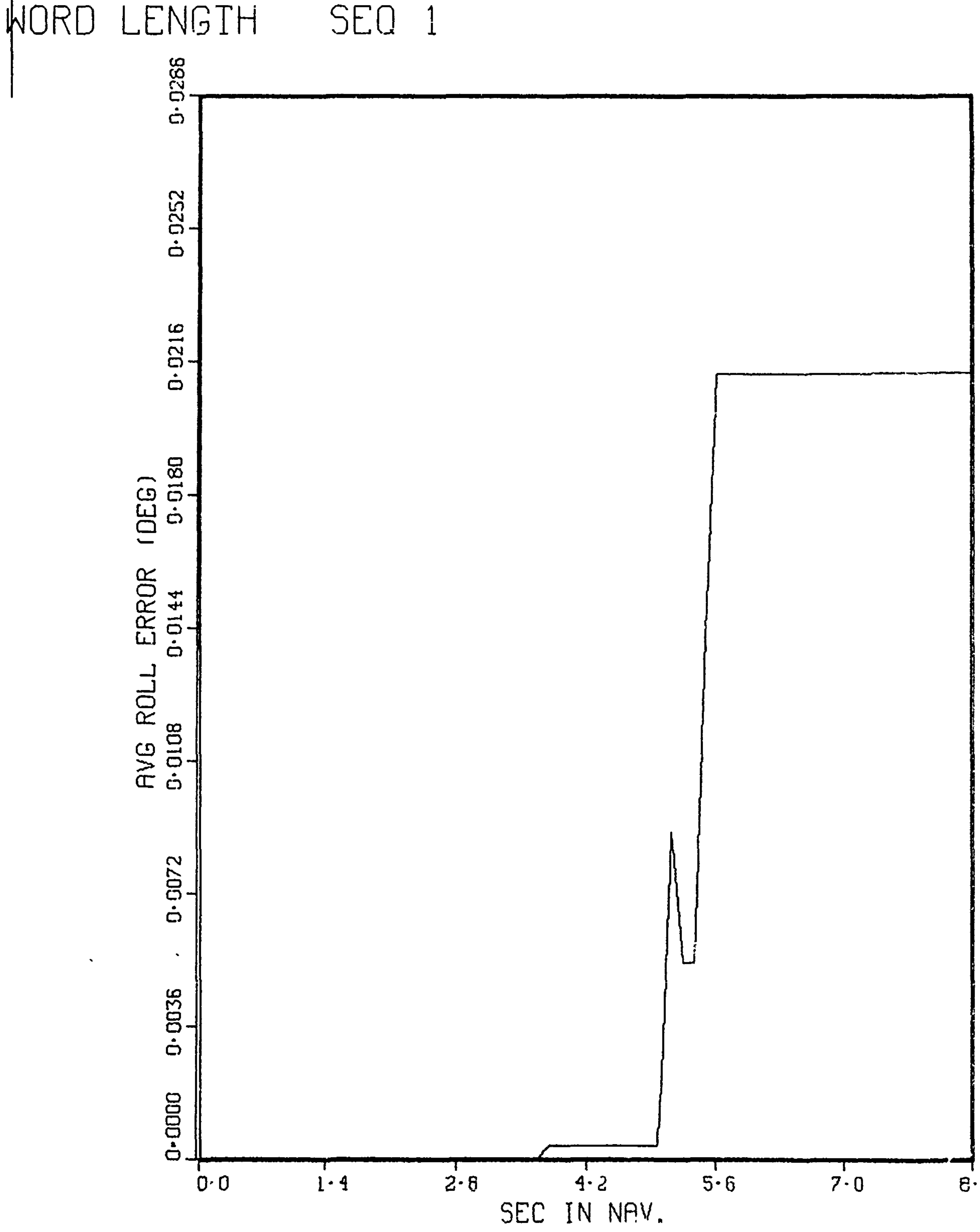


Plot #19

WORD LENGTH SEQ 1

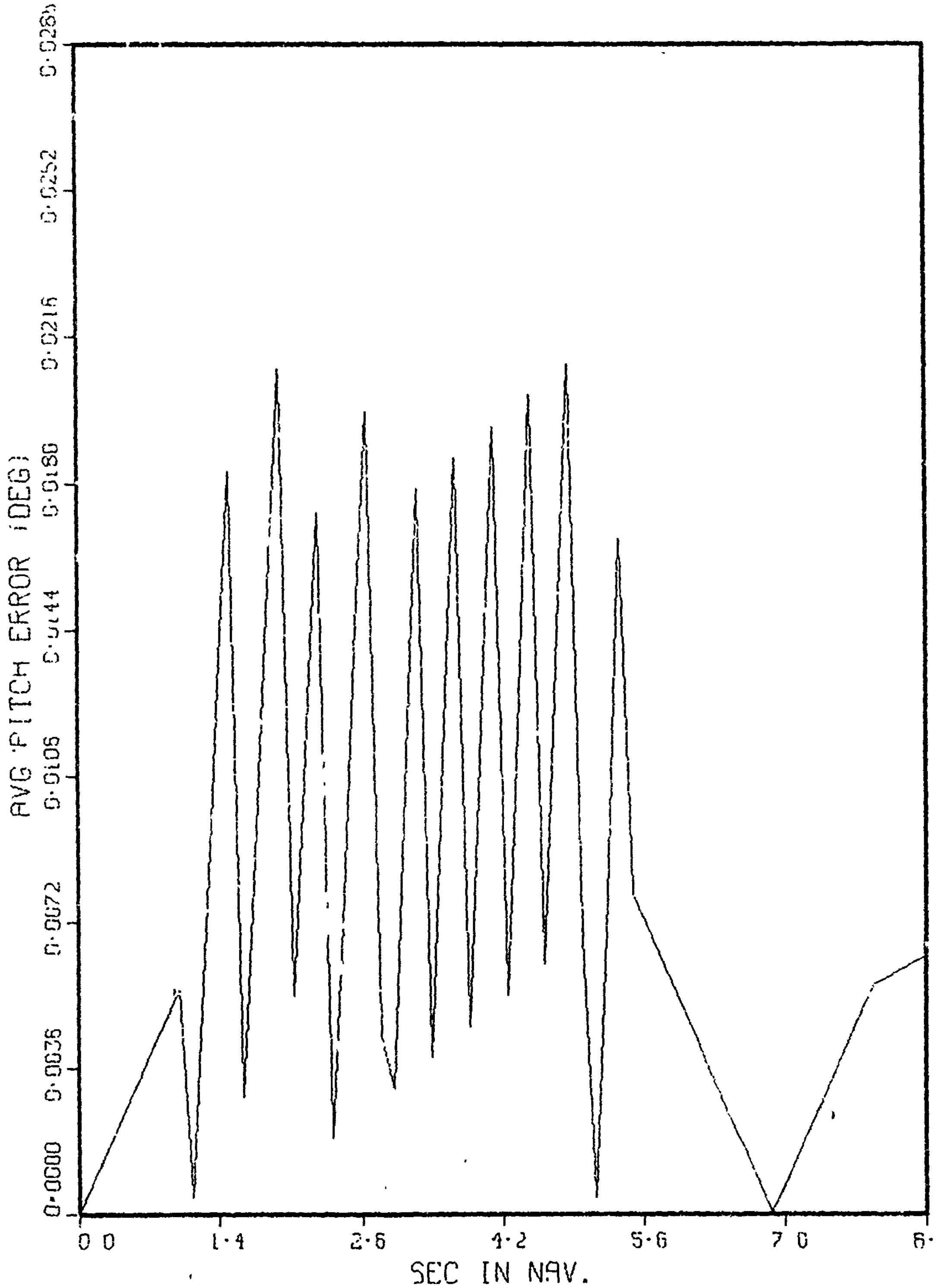


Plot #20


WORD LENGTH SEQ 1
AVG ROLL ERROR (DEG)
0.0288
0.0252
0.0216
0.0180
0.0144
0.0108
0.0072
0.0036
0.0000
0.0
1.4
2.8
4.2
5.6
7.0
8.4
SEC IN NAV.

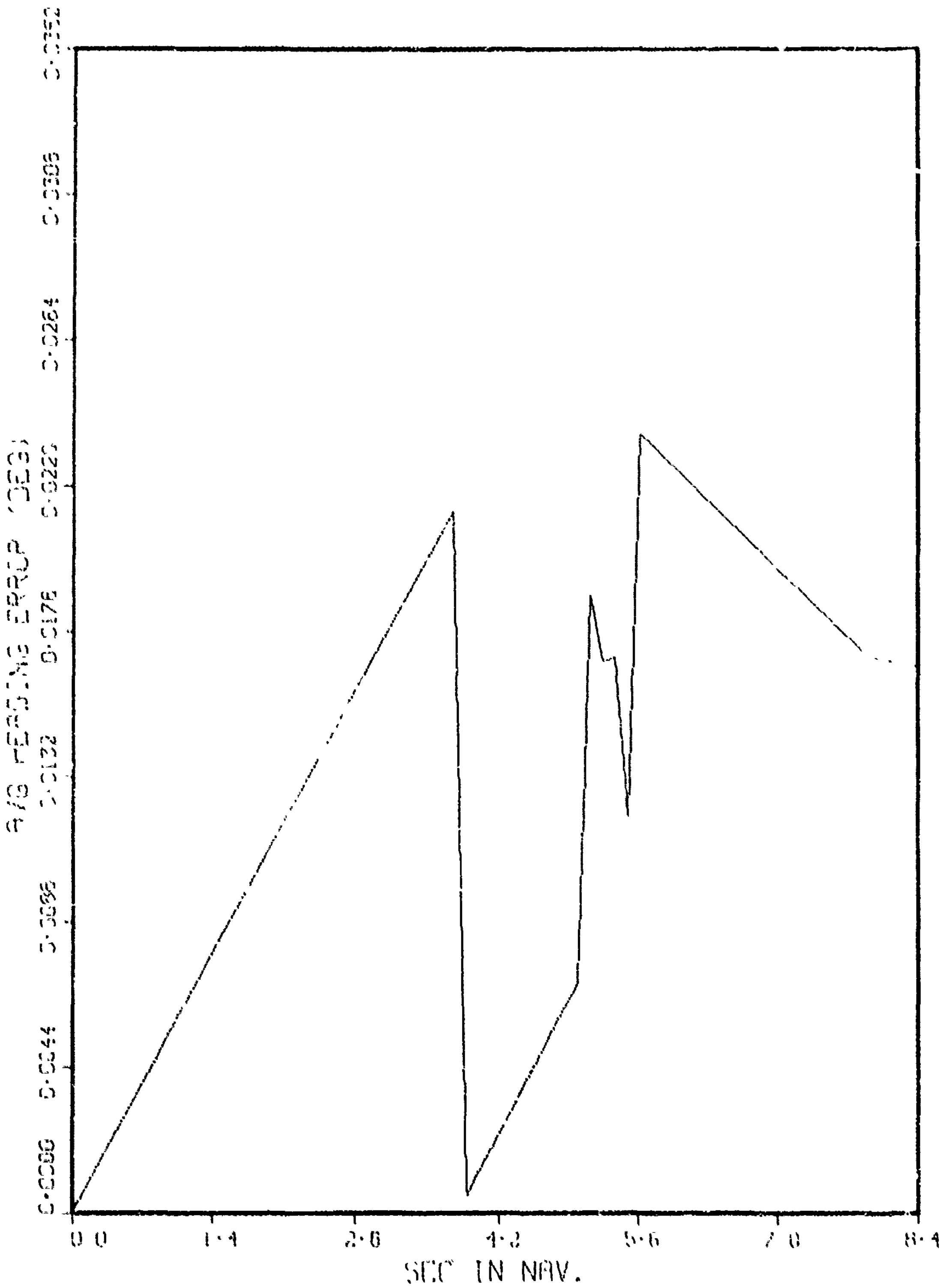
Plot #21

WORD LENGTH SEQ 1



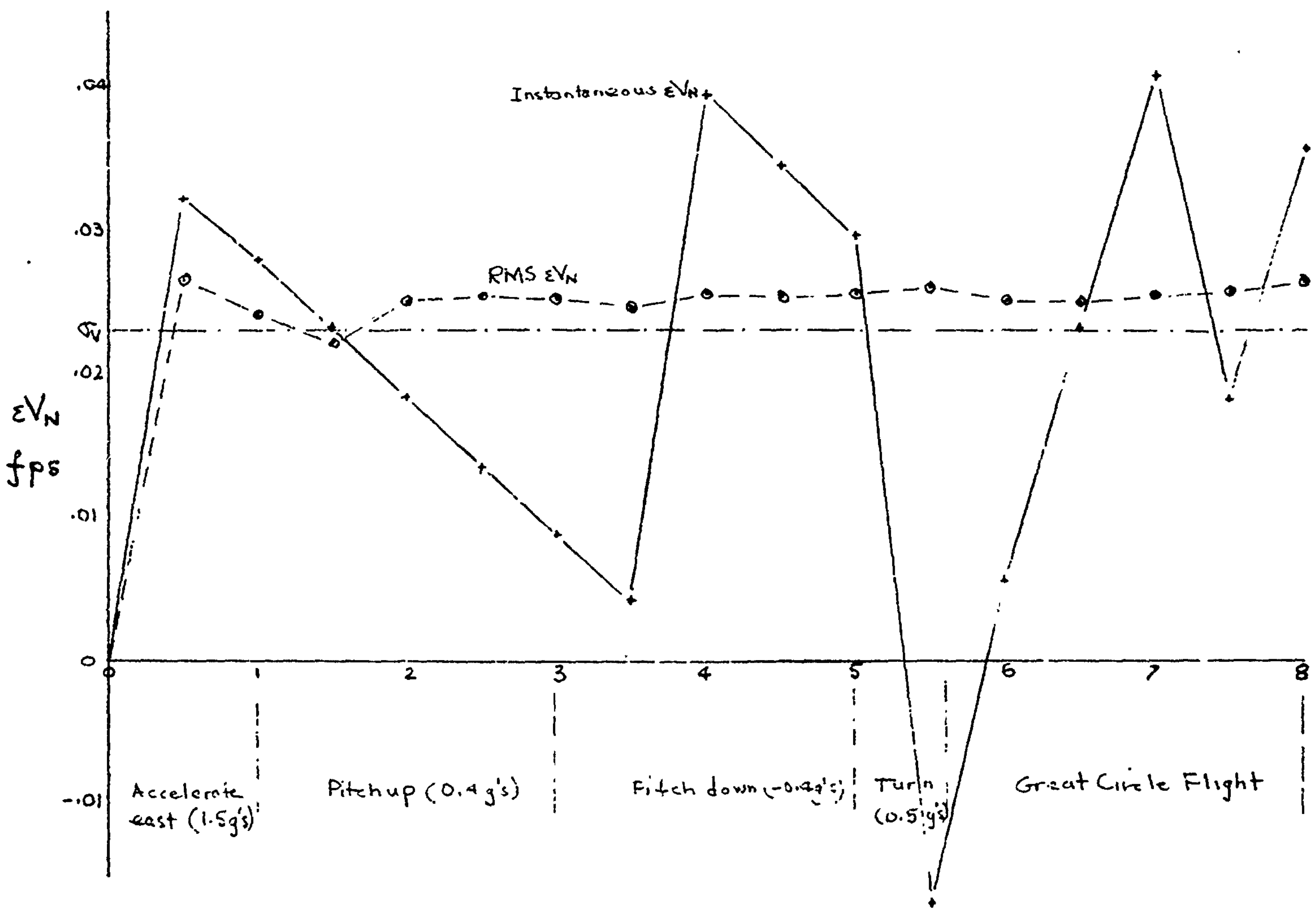
Plot #22

WORD LENGTH SEQ 1



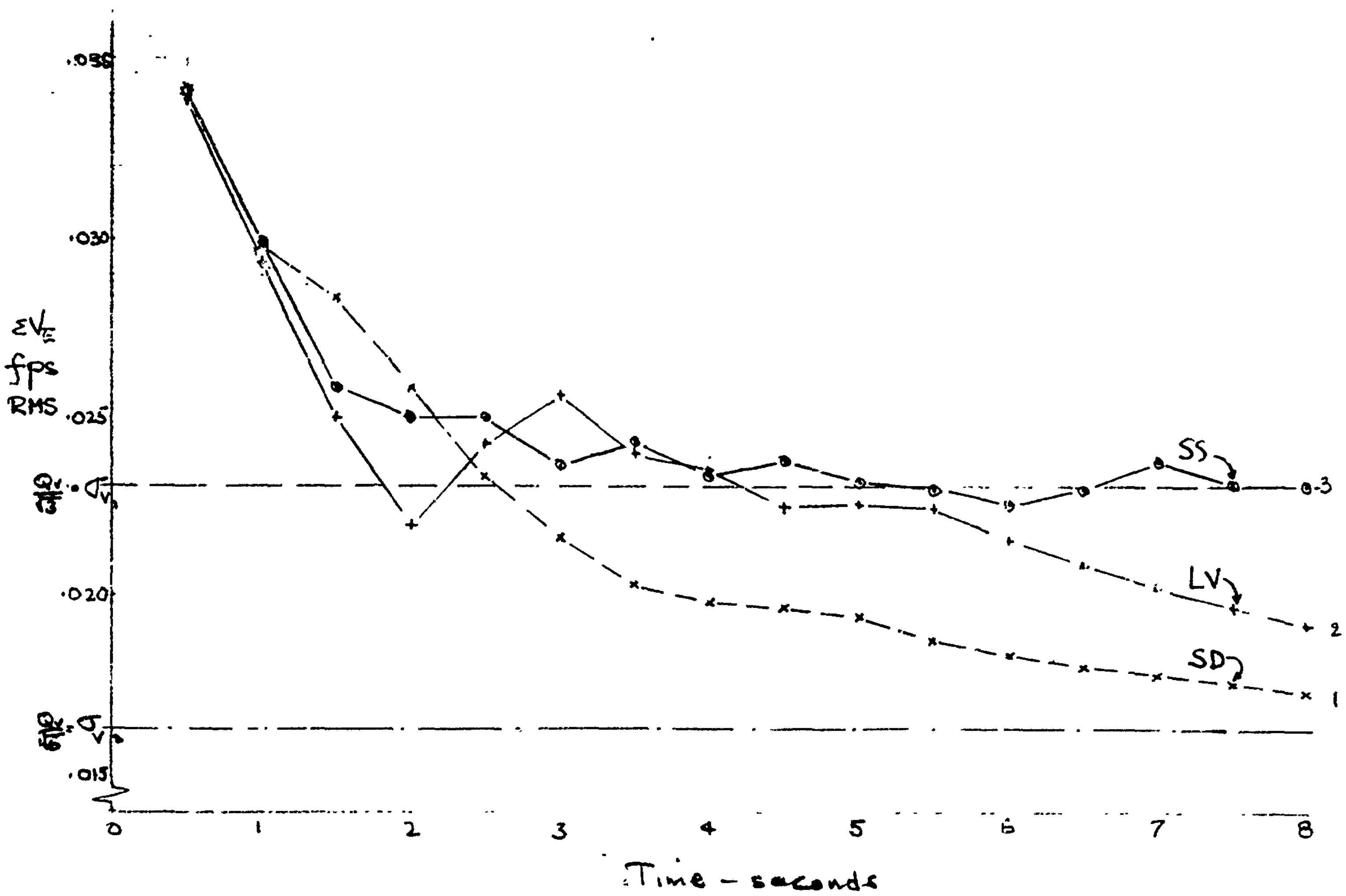
Plot #24
Seq. #1

Instantaneous and RMS North Velocity Errors



RMS E 2.5' Velocity Errors During & Second Flight S.q #1,2,3

Quantization - 0.040 fps/pulse, 0.374 mrad/pulse Plot # 25



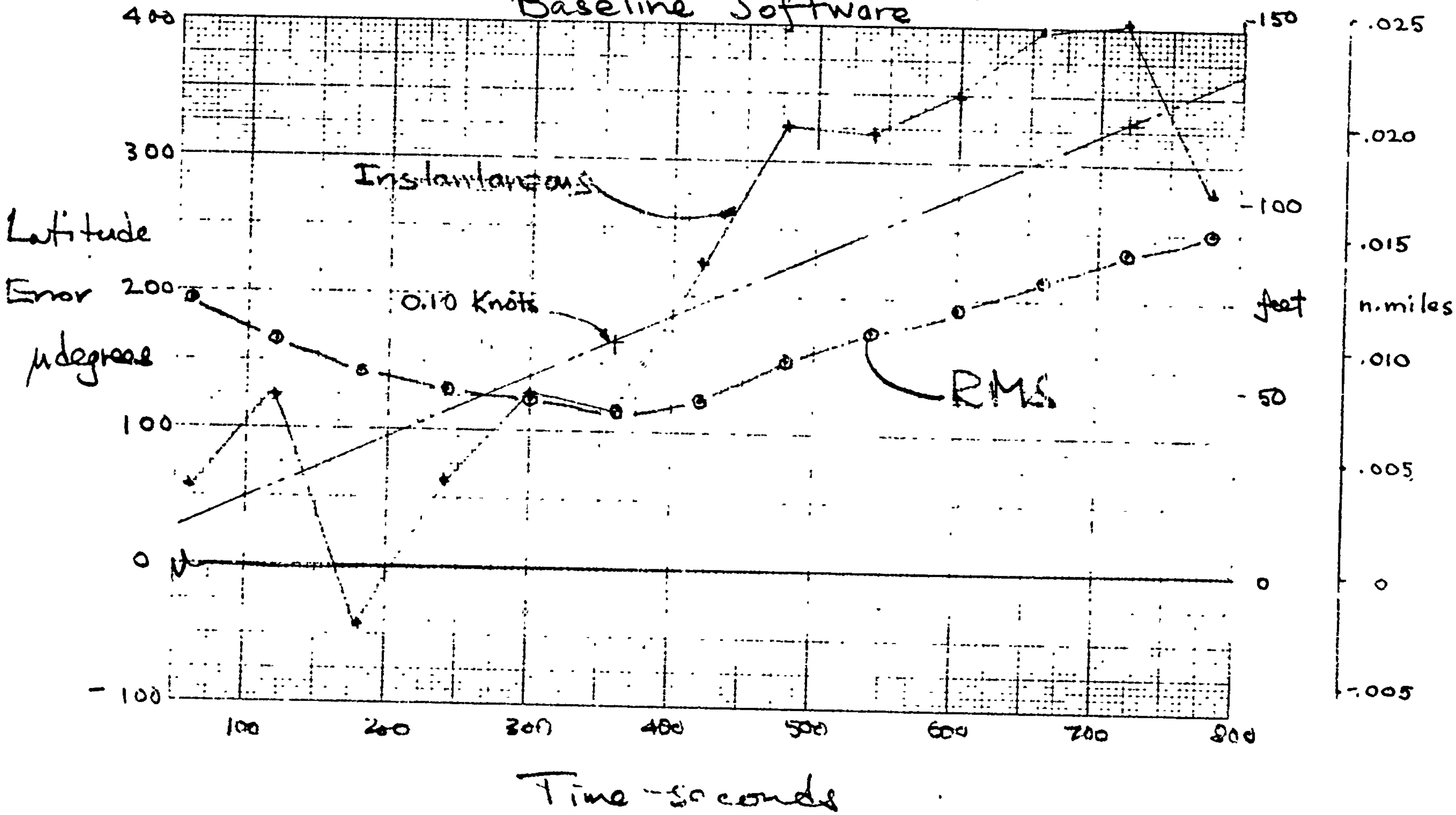
FORM 3 T

Sequence # 16

Plot # 26

Start of F4 Mission (Dynamic)

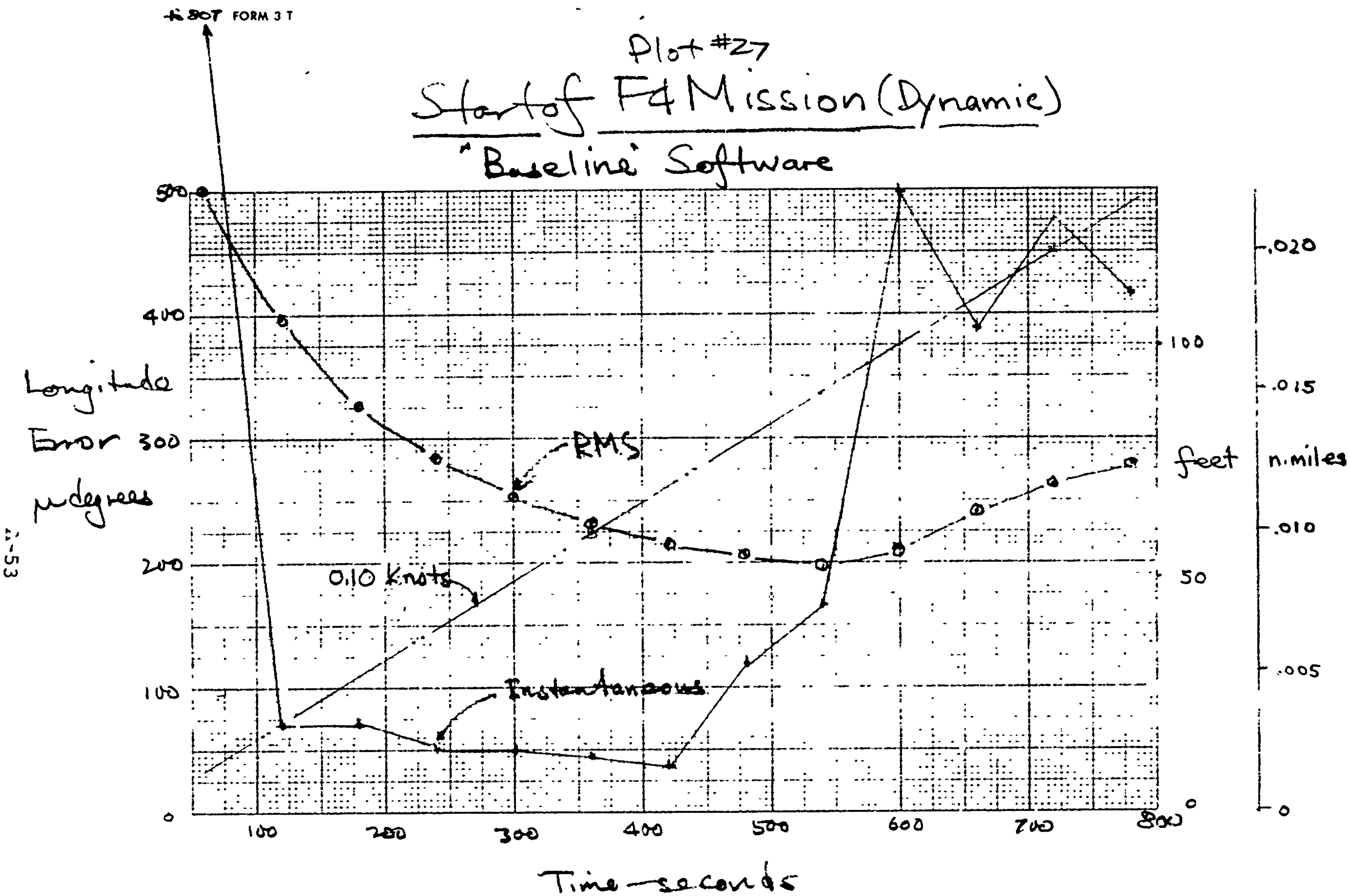
"Baseline" Software



Plot #27

Start of F4 Mission (Dynamic)

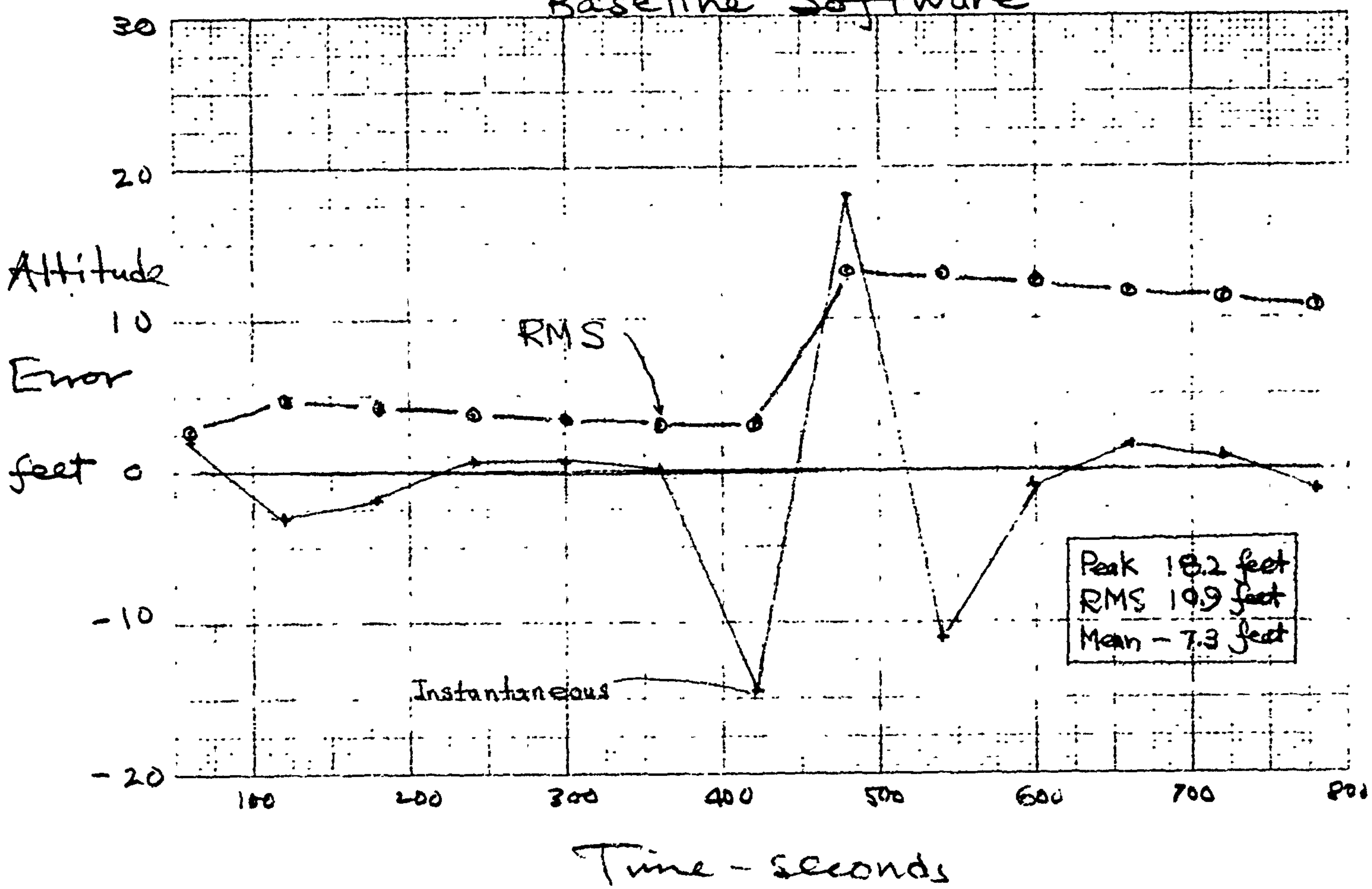
"Baseline" Software



FORM 3 T

Plot #28 2

Start of F4 Mission (Dynamic)
"Baseline" Software

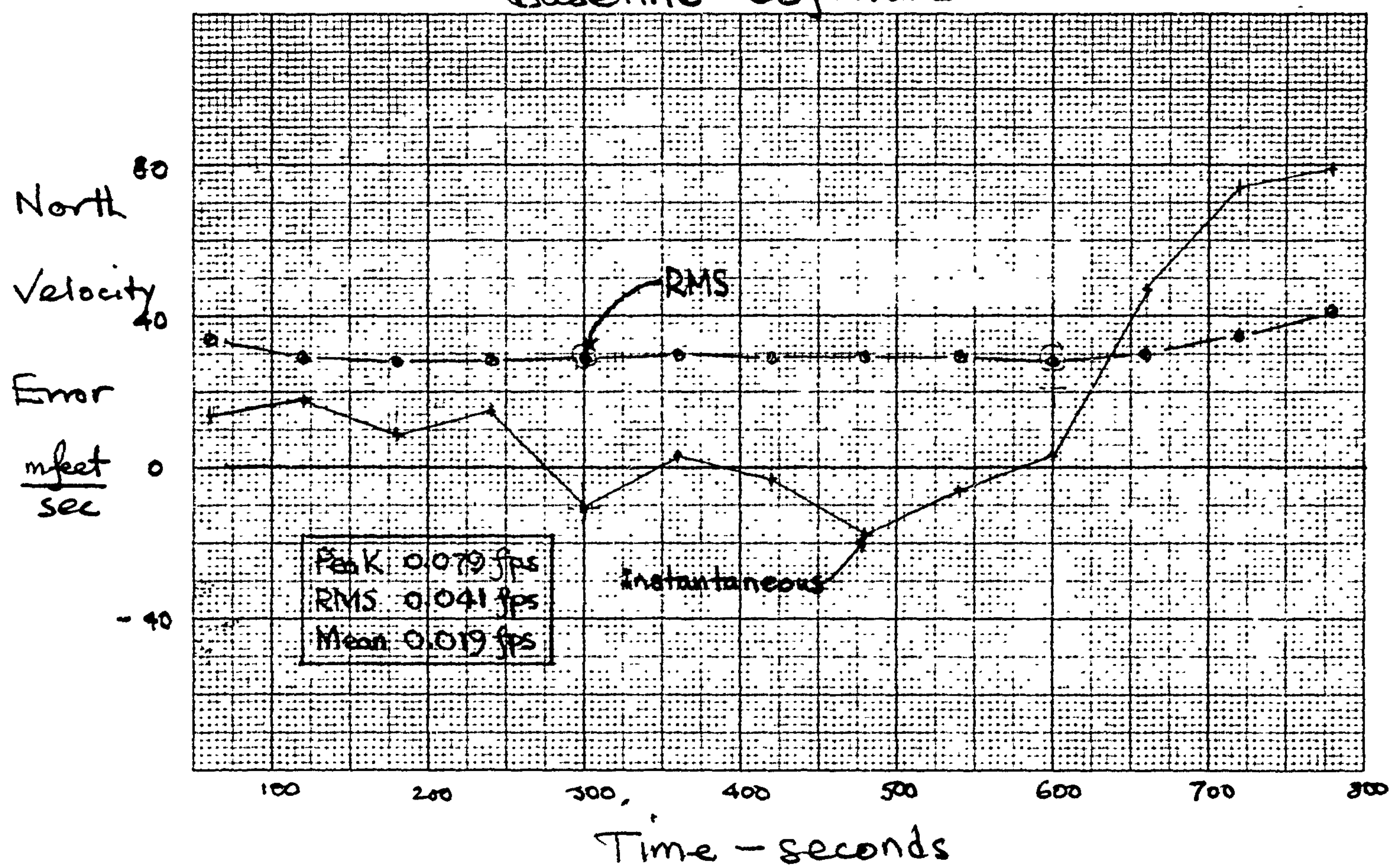


FORM 3 T

Plot #29

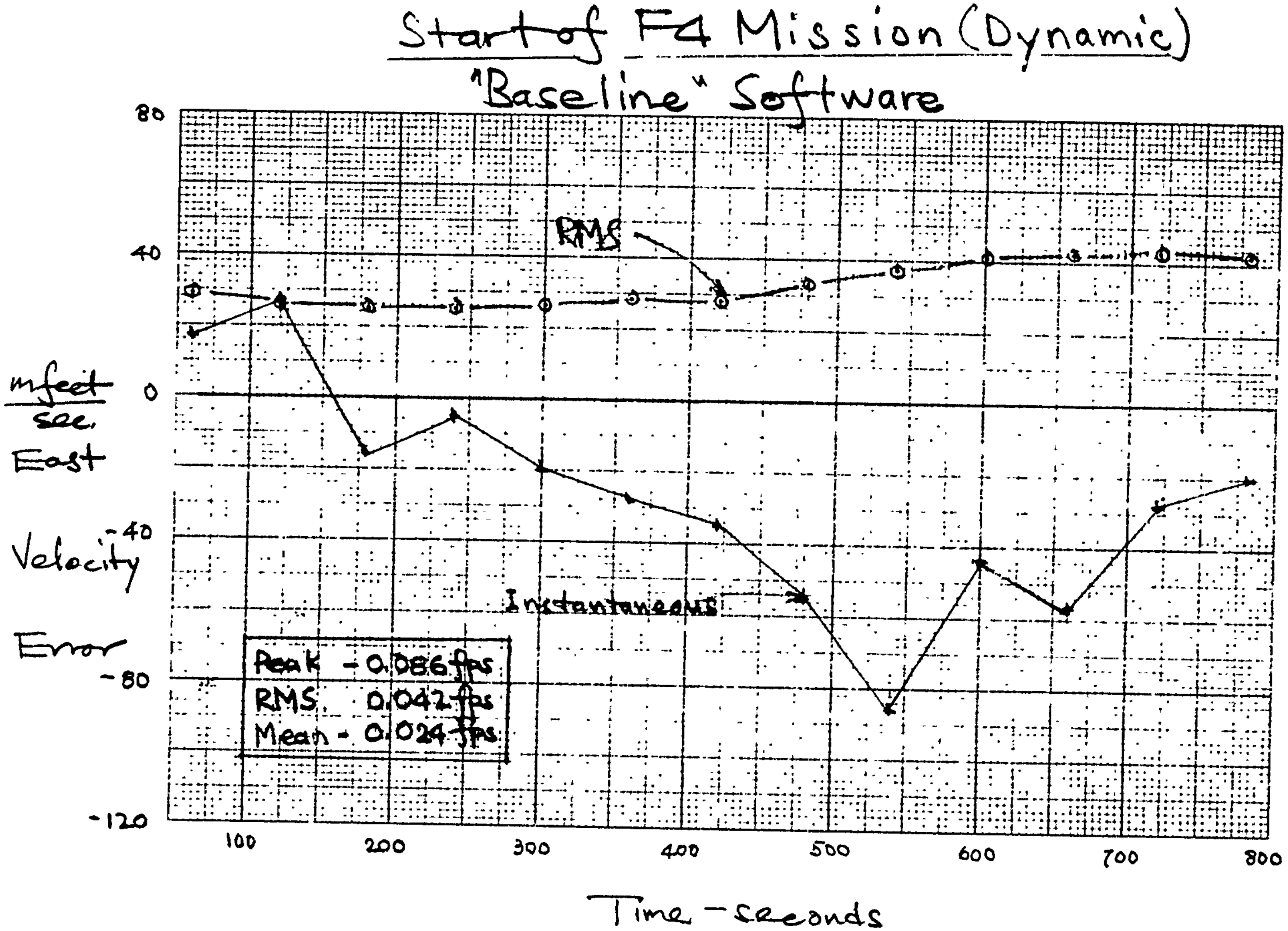
Start of F4 Mission (Dynamics)

"Baseline" Software



FORM 3 T

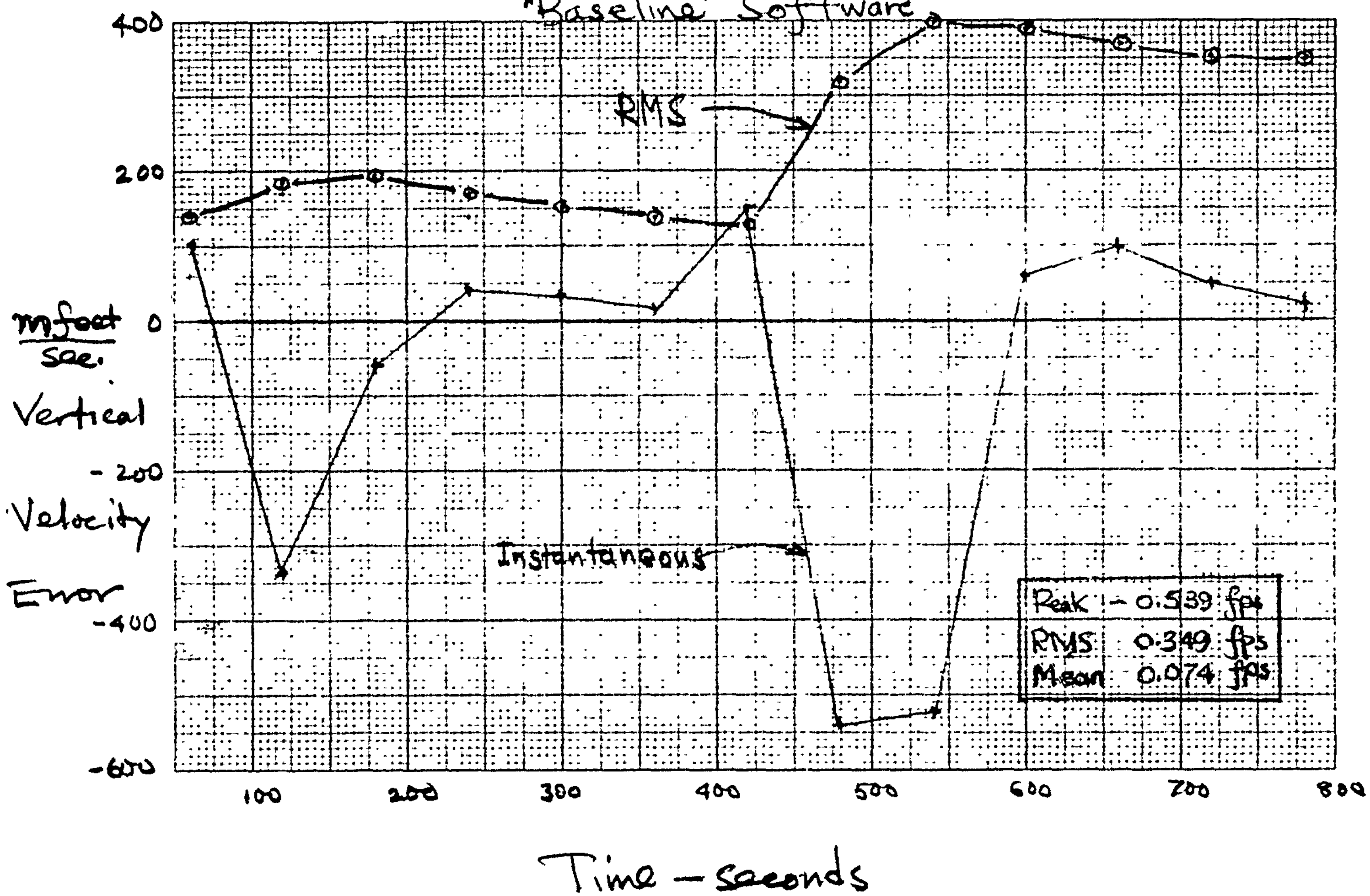
Plot #30



FORM 3 T

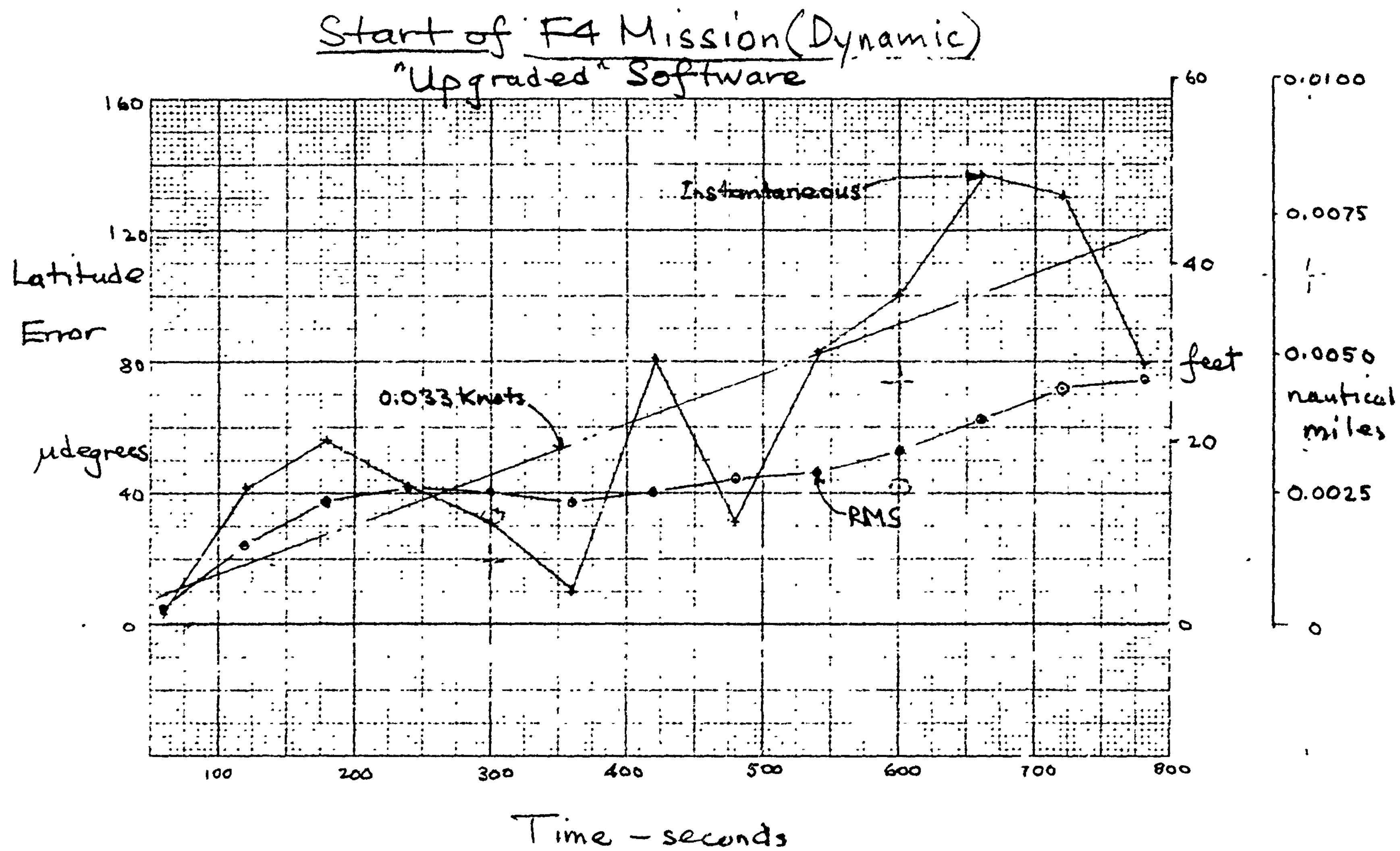
Plot #31

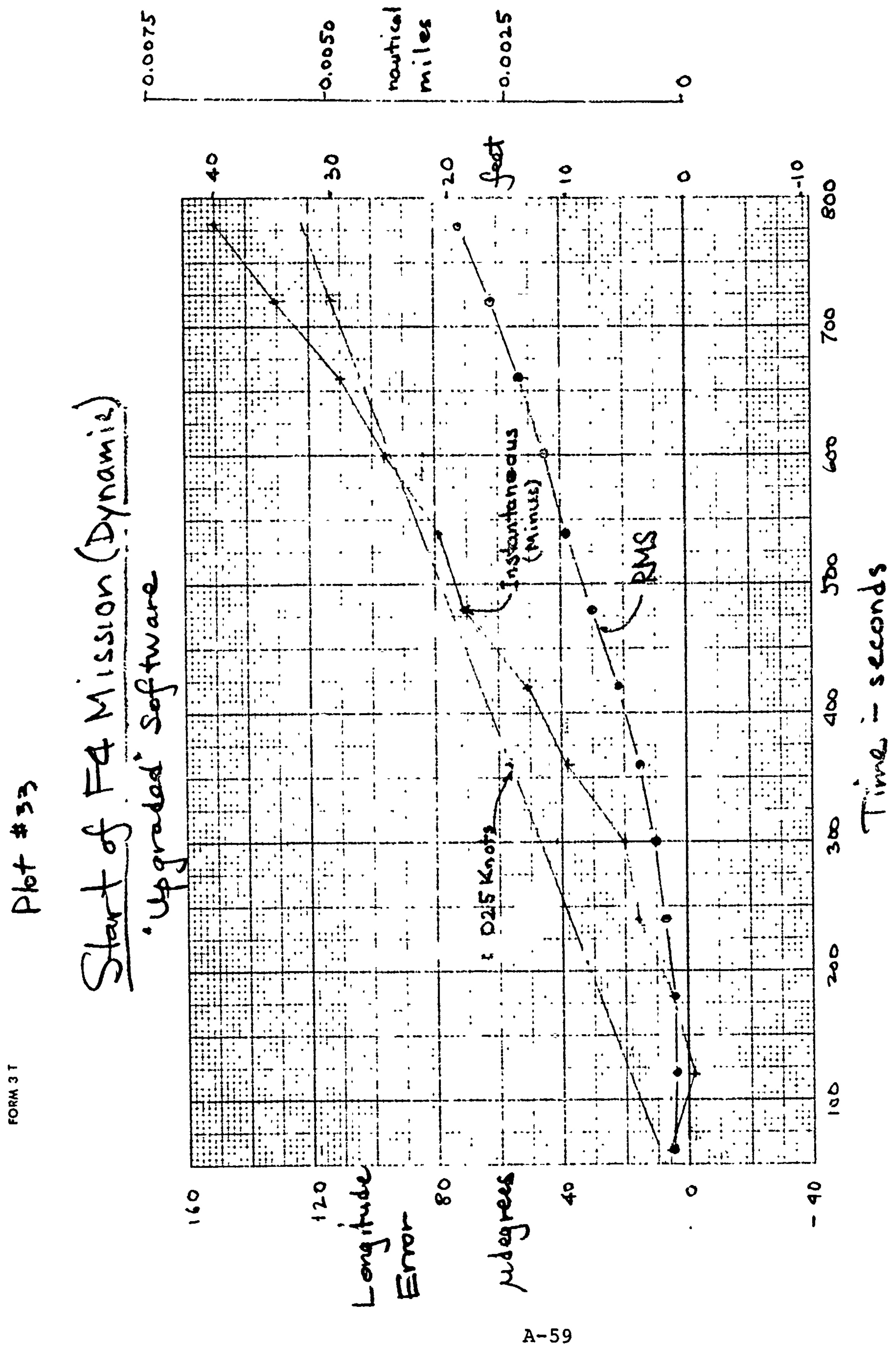
Start of F4 Mission (Dynamic)
"Baseline" Software



FORM 3 T

Plot #32





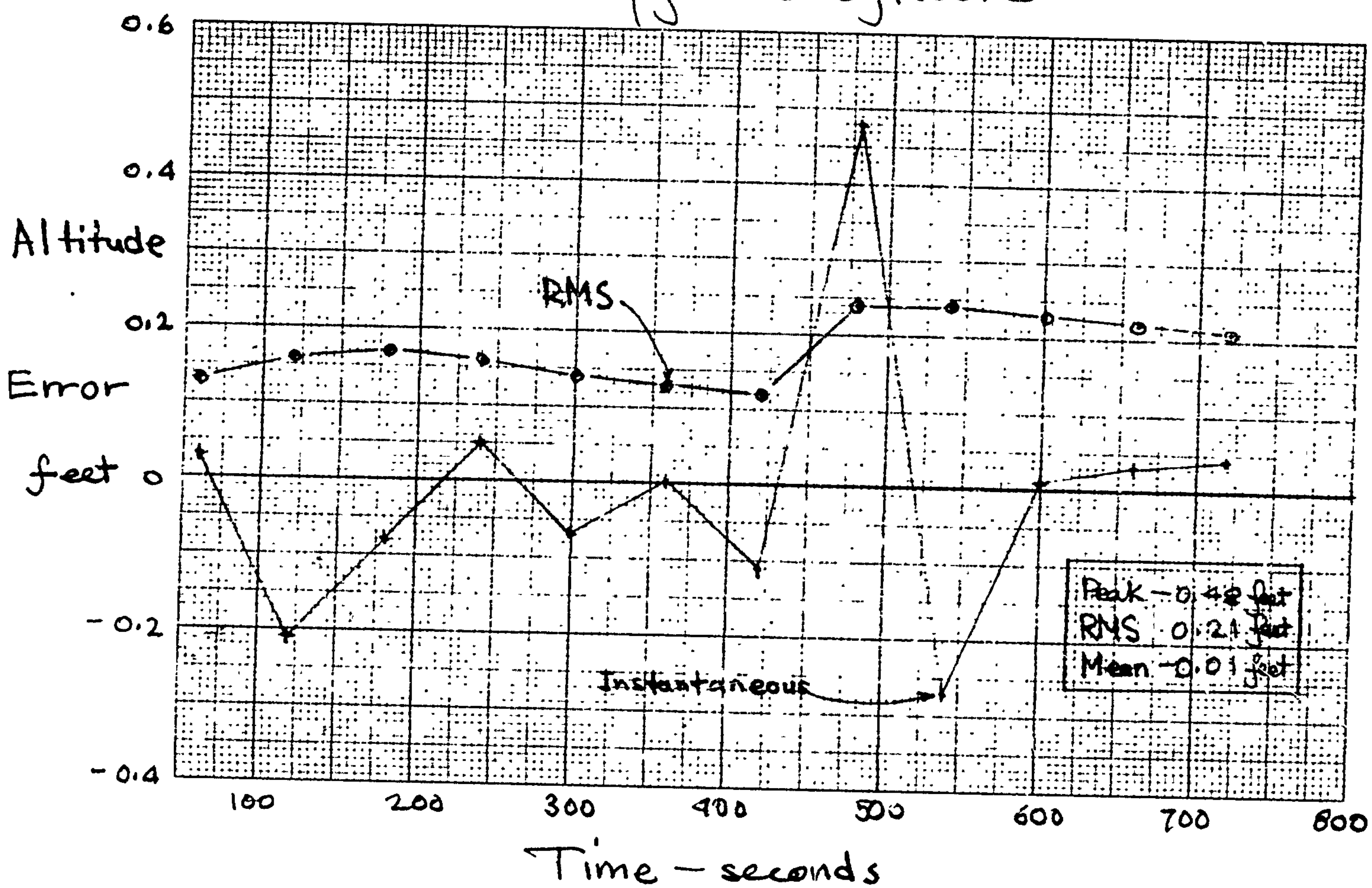
FORM 3 T
Plot #33
Start of F4 Mission (Dynamic)
"Upgraded" Software
Longitude Error
μdegrees
160
120
80
40
0
-40
feet
40
30
20
10
0
-10
nautical miles
0.0075
0.0050
0.0025
0
Instantaneous (Minus)
RMS
0.25 Knots
100
200
300
400
500
600
700
800
Time – seconds

FORM 3 T

Plot #34

Start of F4 Mission (Dynamic)

"Upgraded" Software

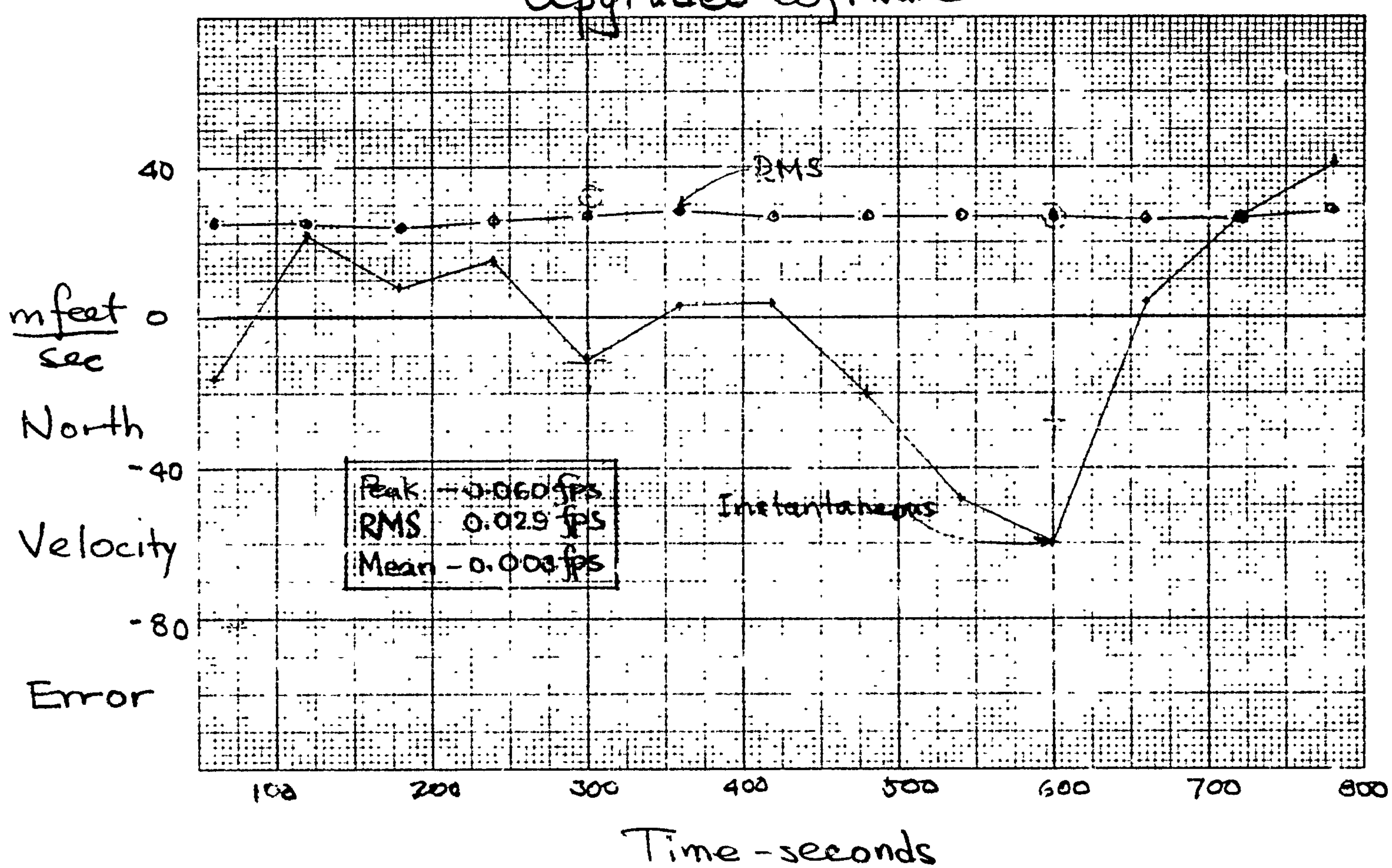


FORM 3 T

Plot #35

Start of F4 Run (Dynamic)

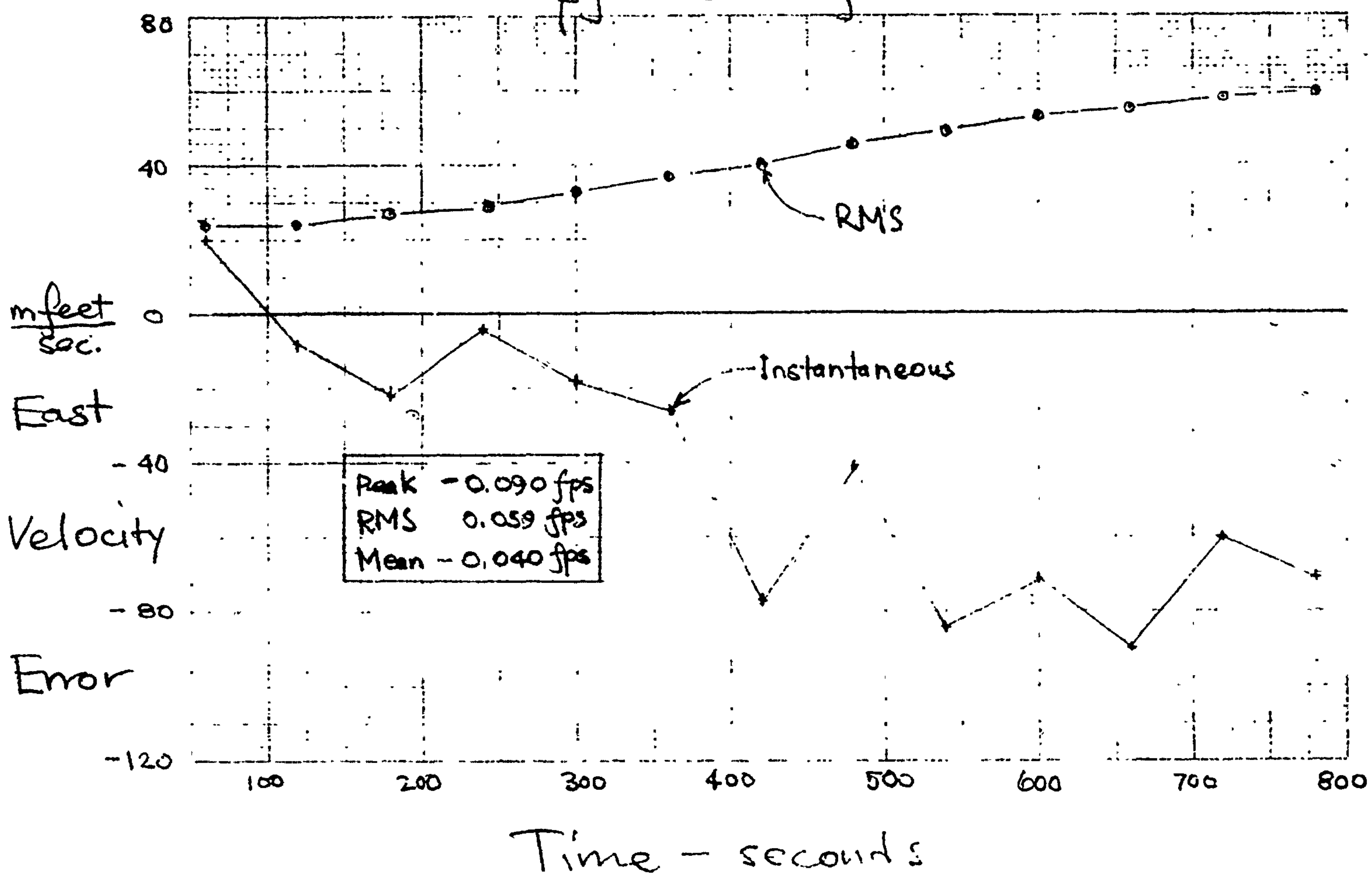
"Upgraded" Software



FORM 3 T

Plot #36

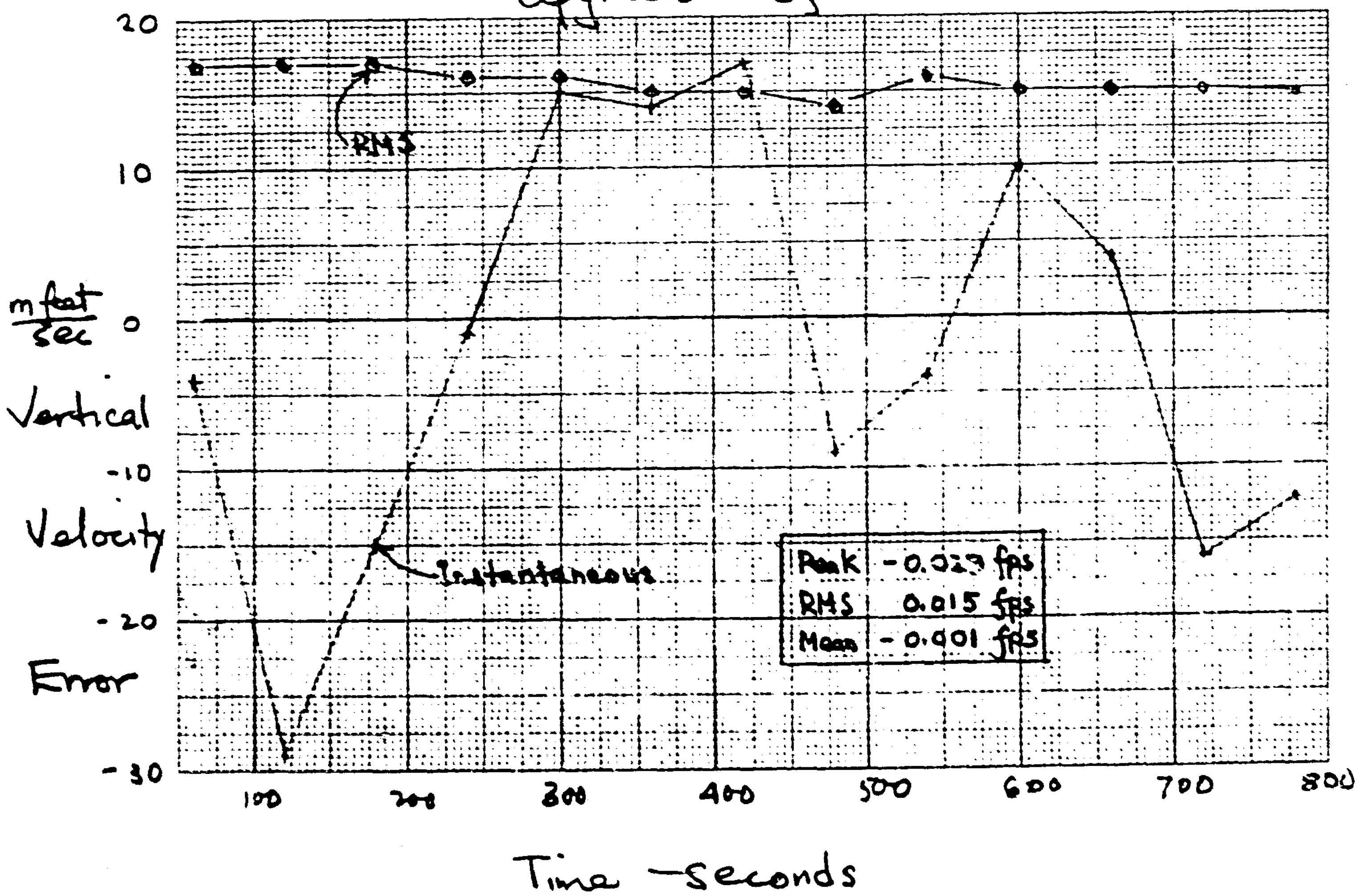
Start of F4 Mission (Dynamic)
"Upgraded" Software



FORM 3 T

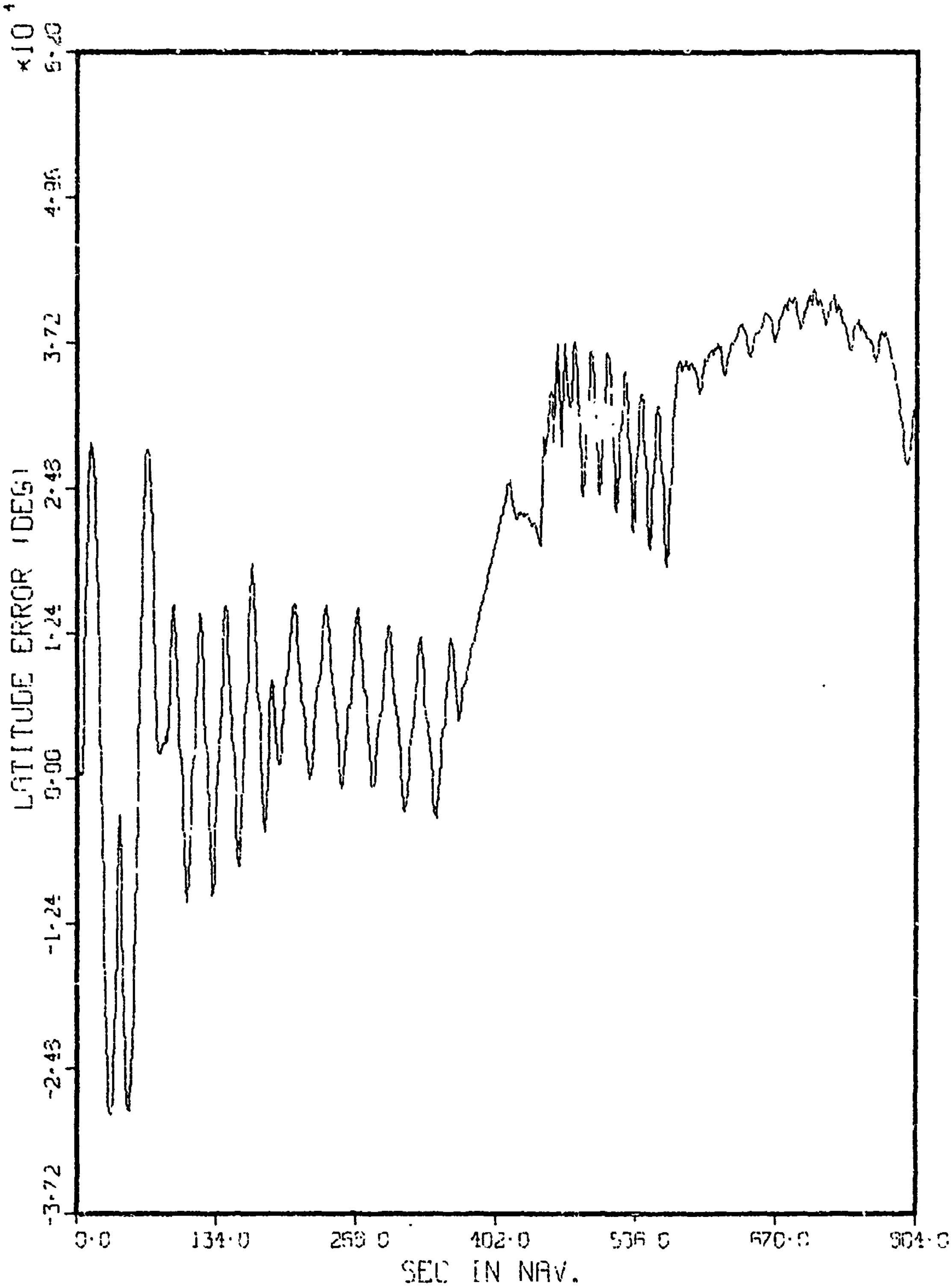
Plot #37

Start of F4 Mission (Dynamic)
"Upgraded" Software



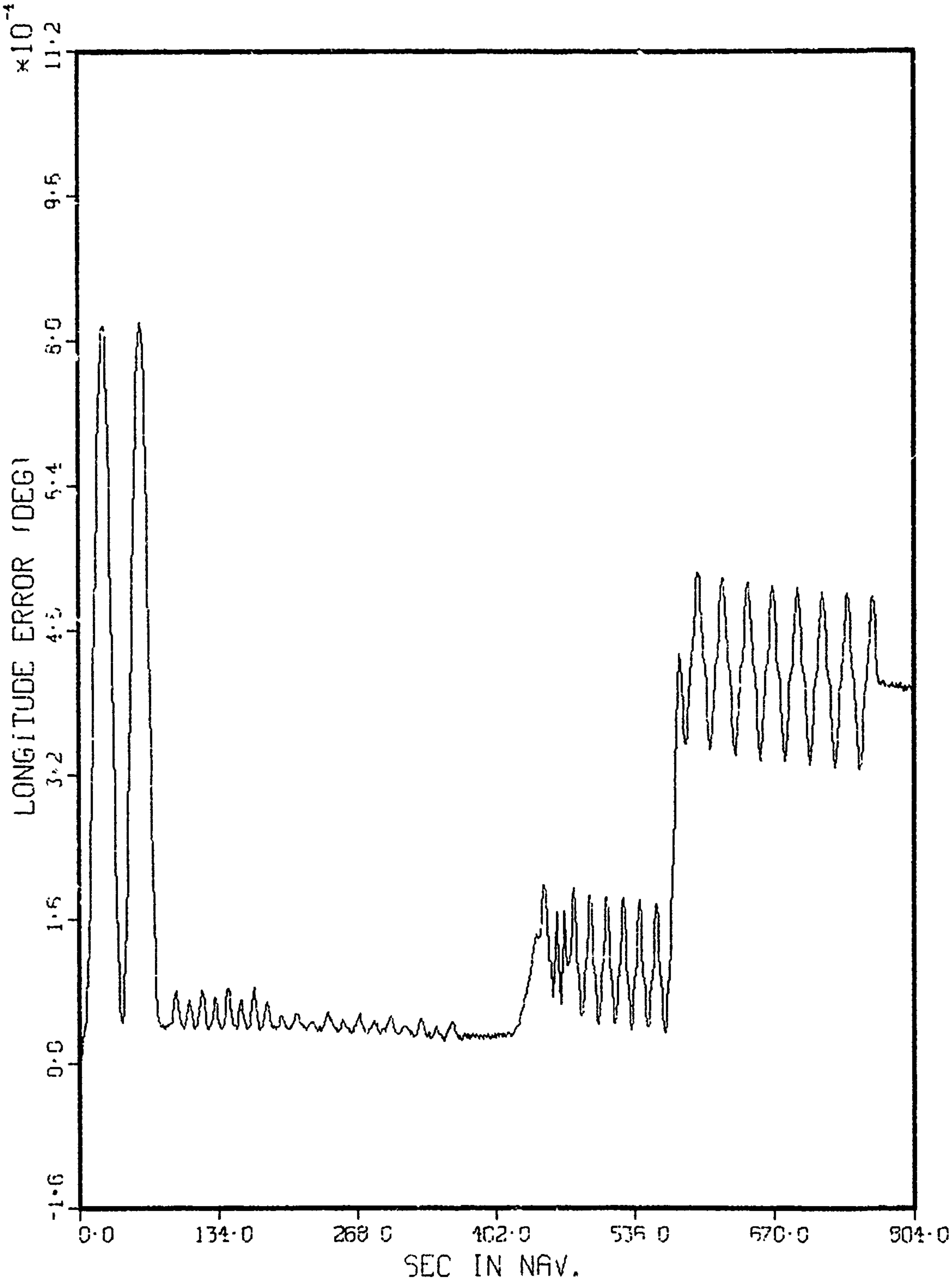
Plot #38

LONG F4 RUN BASE S/W SEQ 16



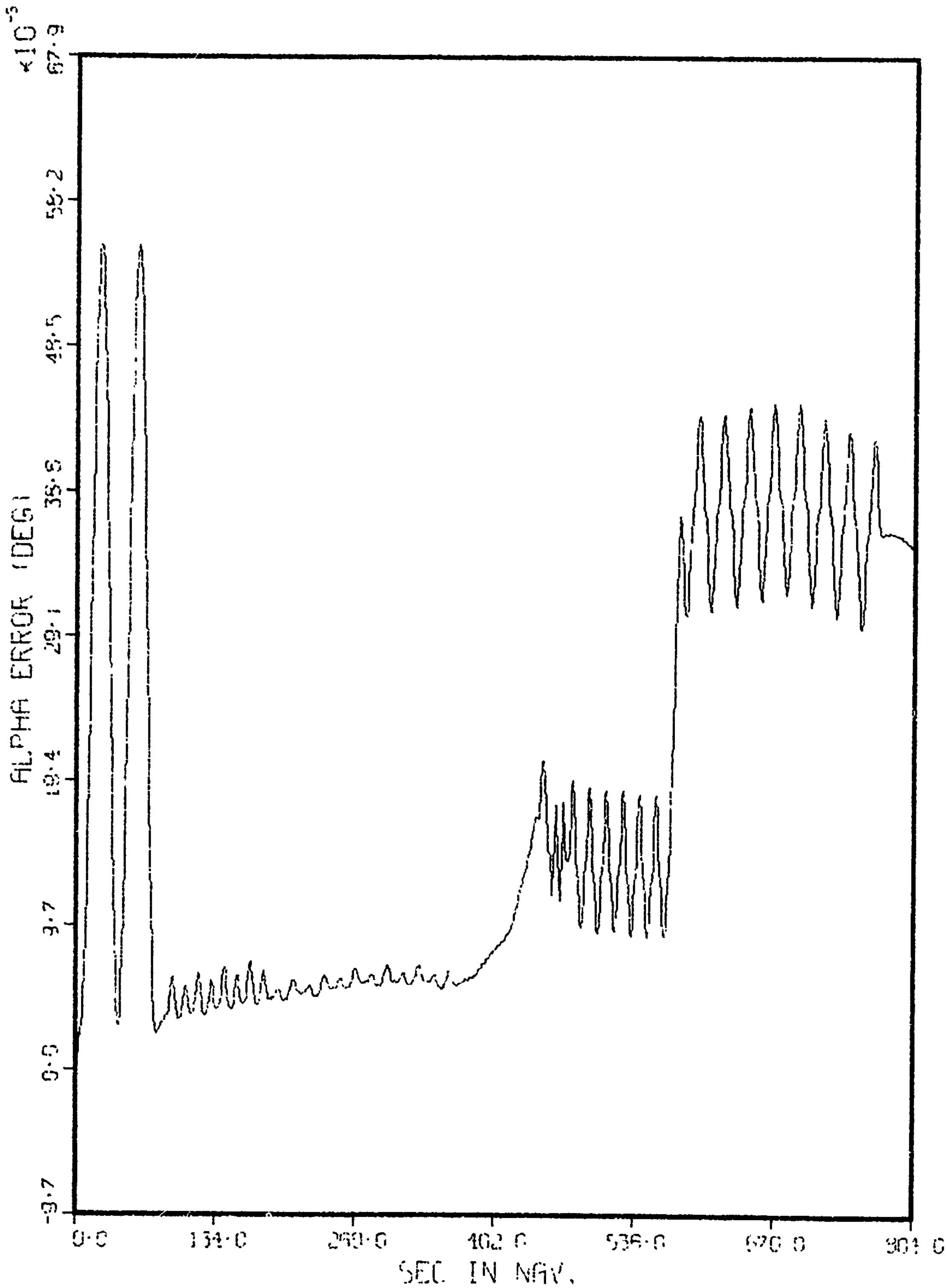
Plot #39

LONG F4 RUN BASE S/W SEQ 16



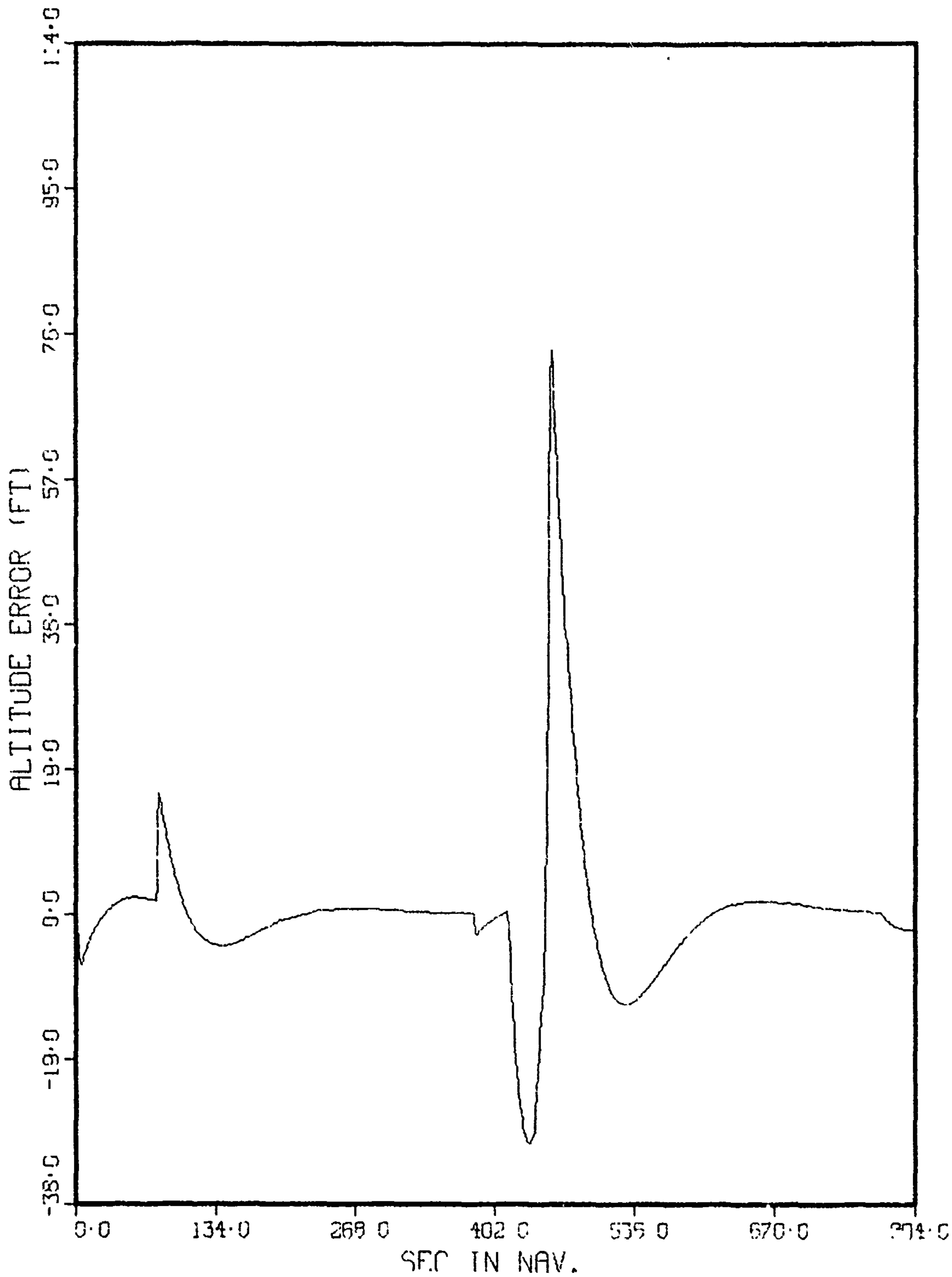
Plot #40

LONG F4 RUN BASE S/W SEQ 16



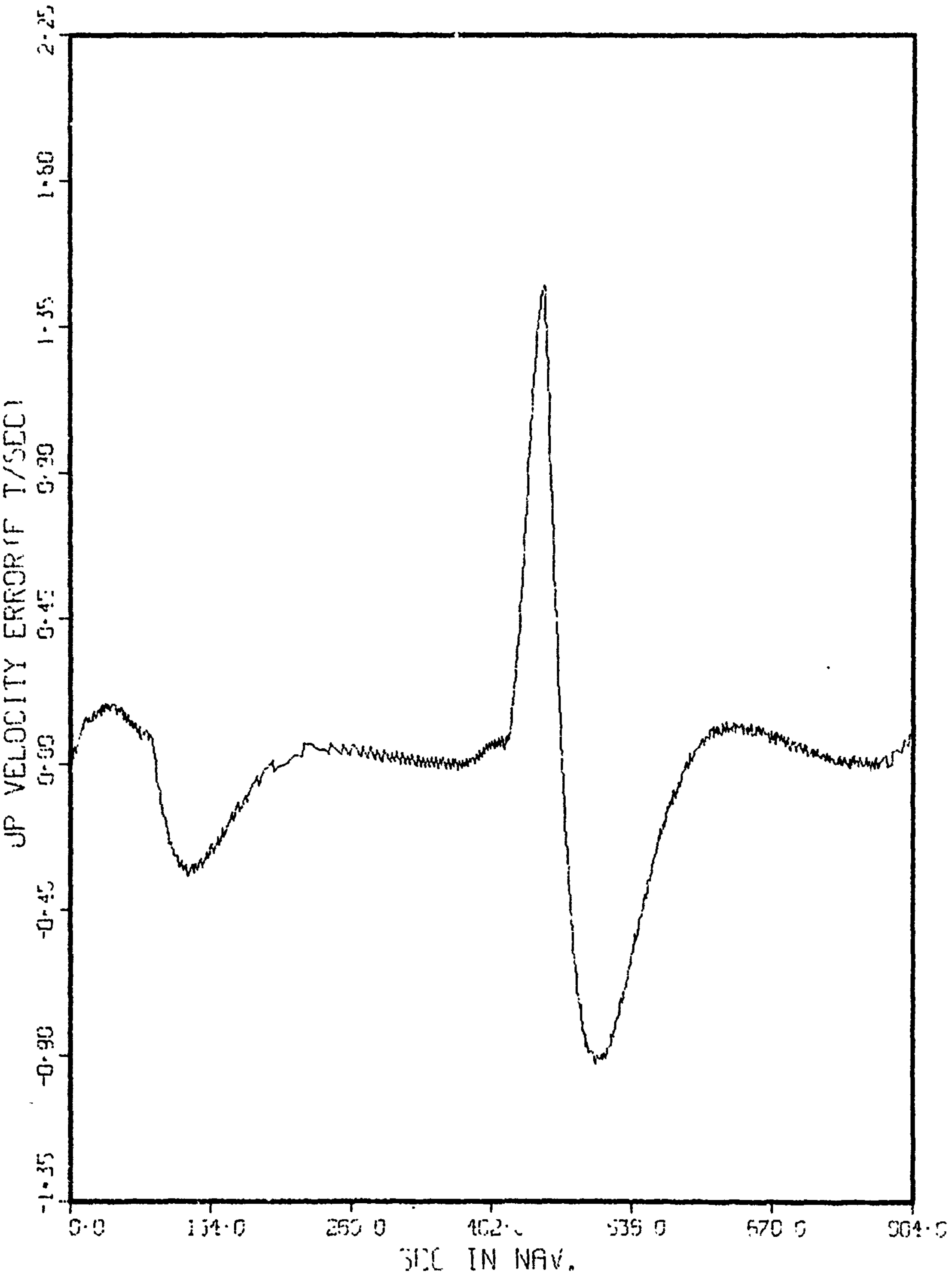
Plot #41

LONG F4 RUN BASE S/W SEQ 16



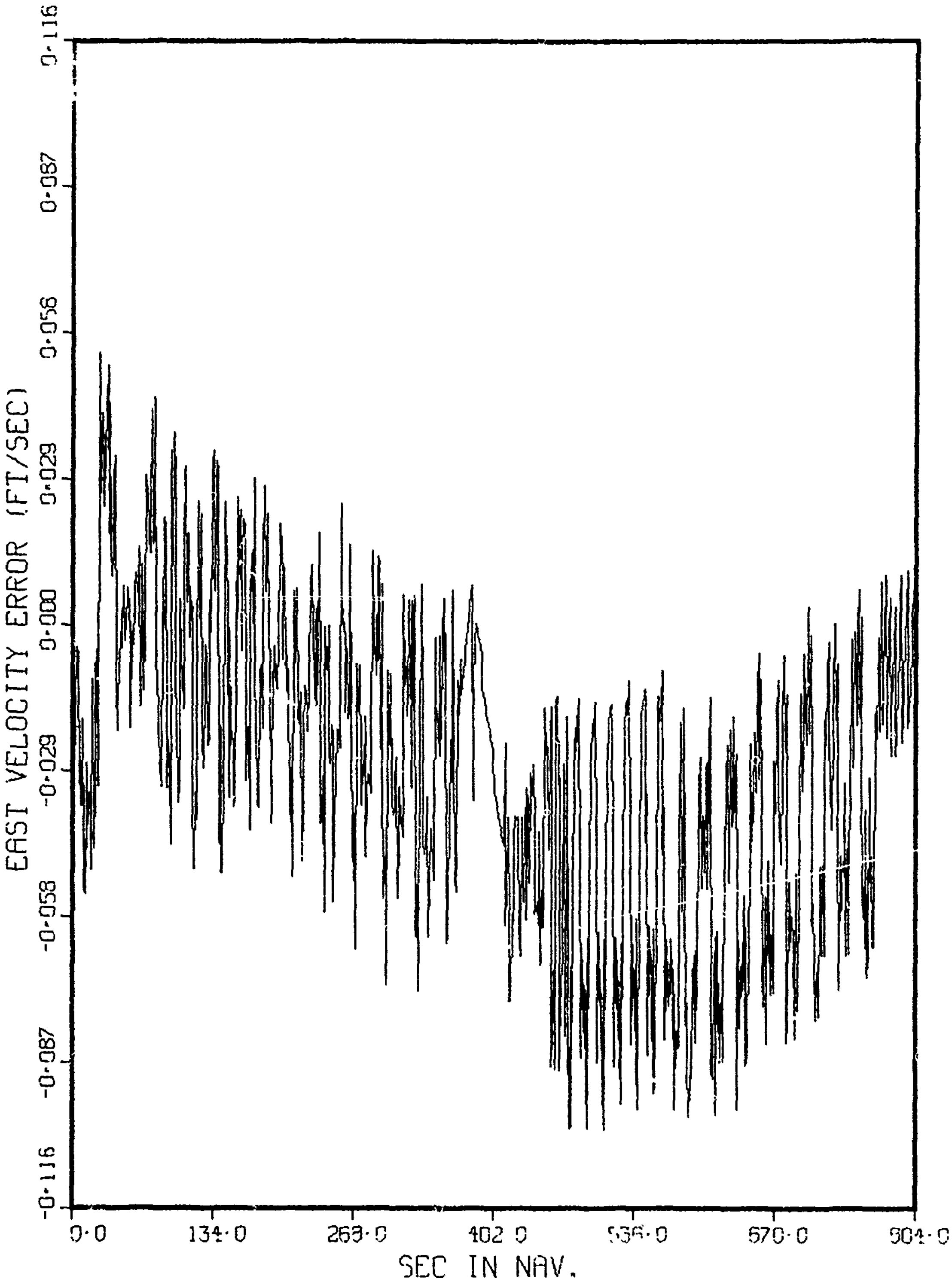
Plot #42

LONG F4 RUN BASE S/W SEO 16



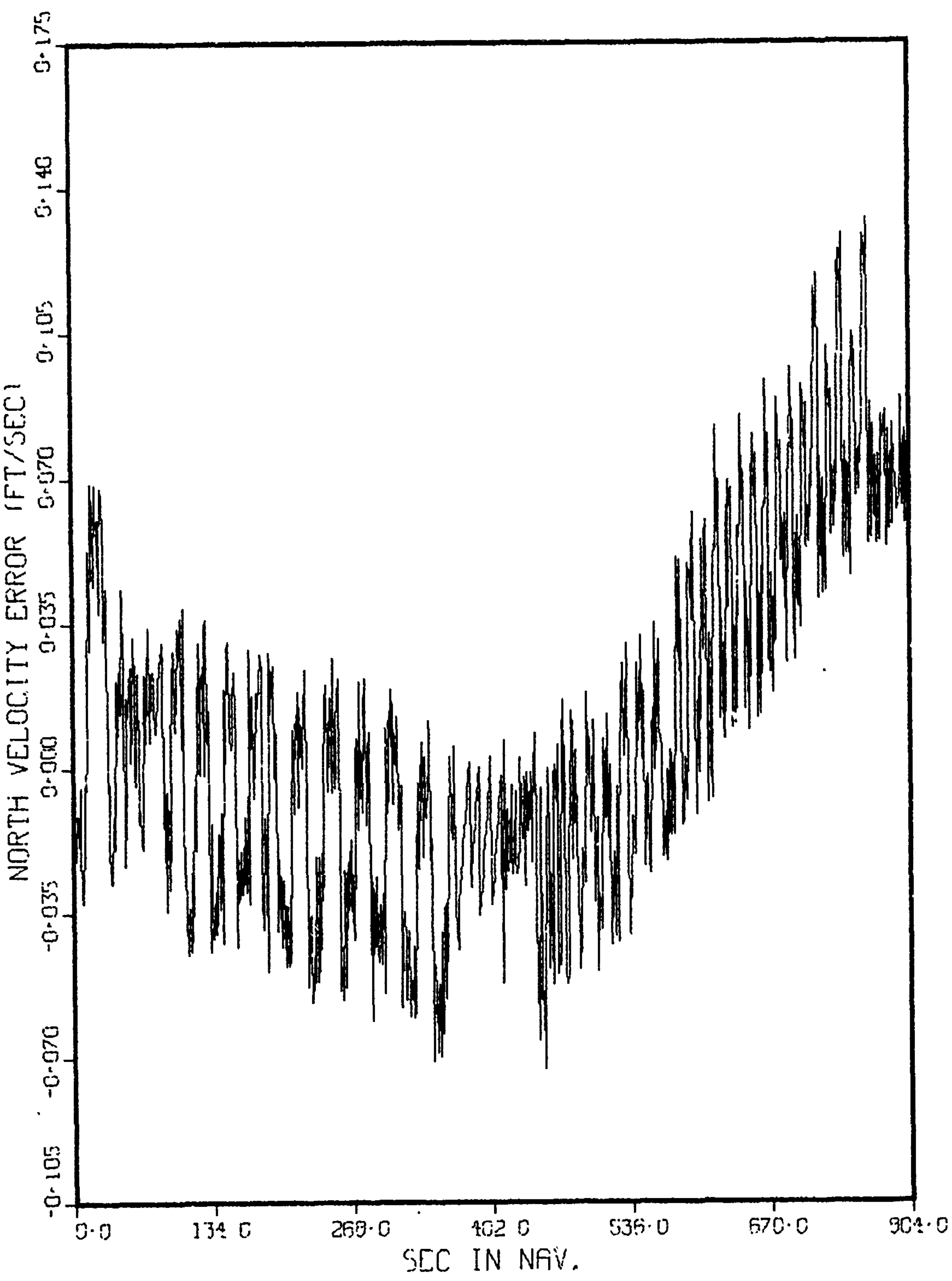
Plot #43

LONG F4 RUN BASE S/W SEQ 16

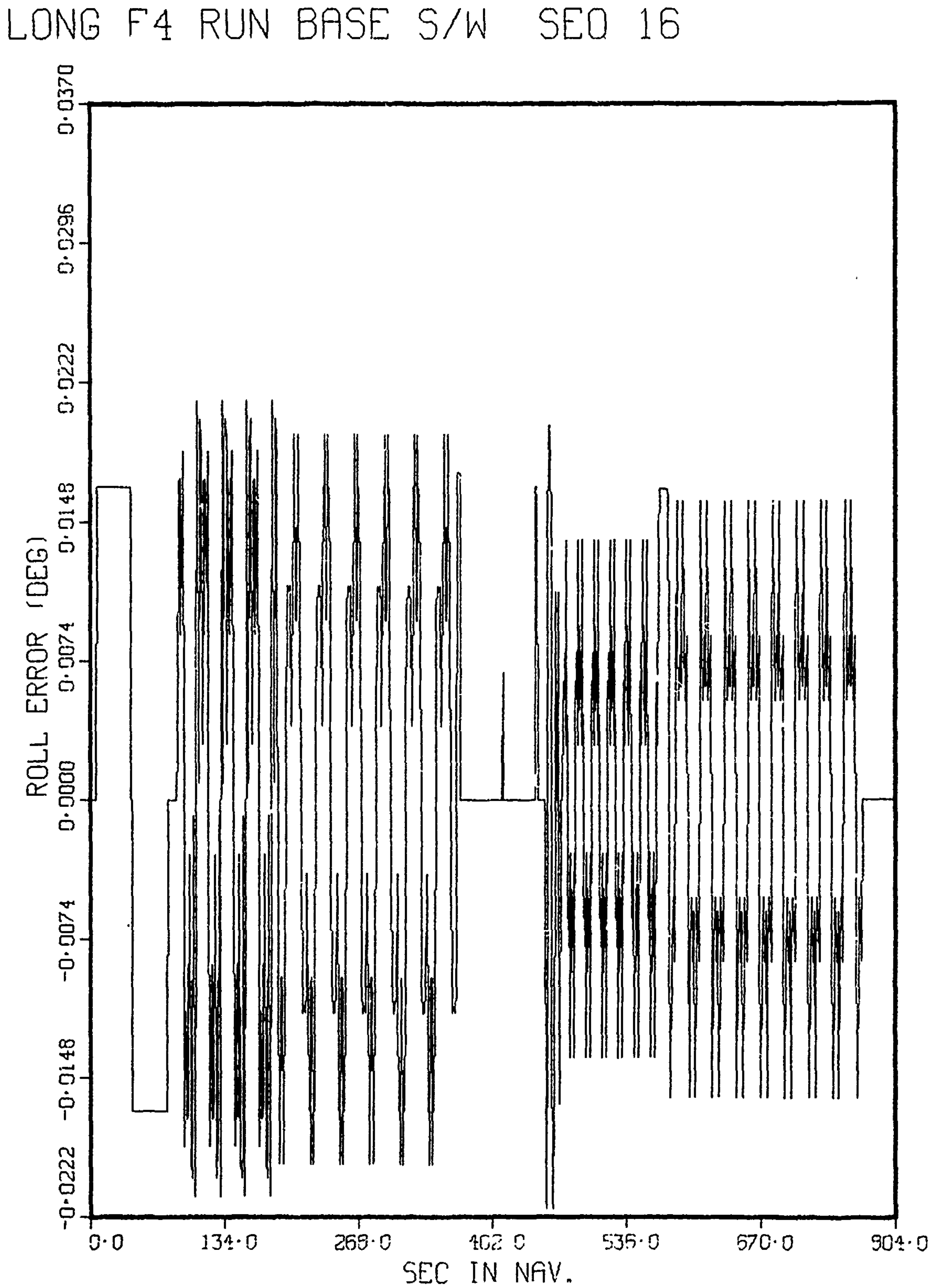


Plot #44

LONG F4 RUN BASE S/W SEQ 16



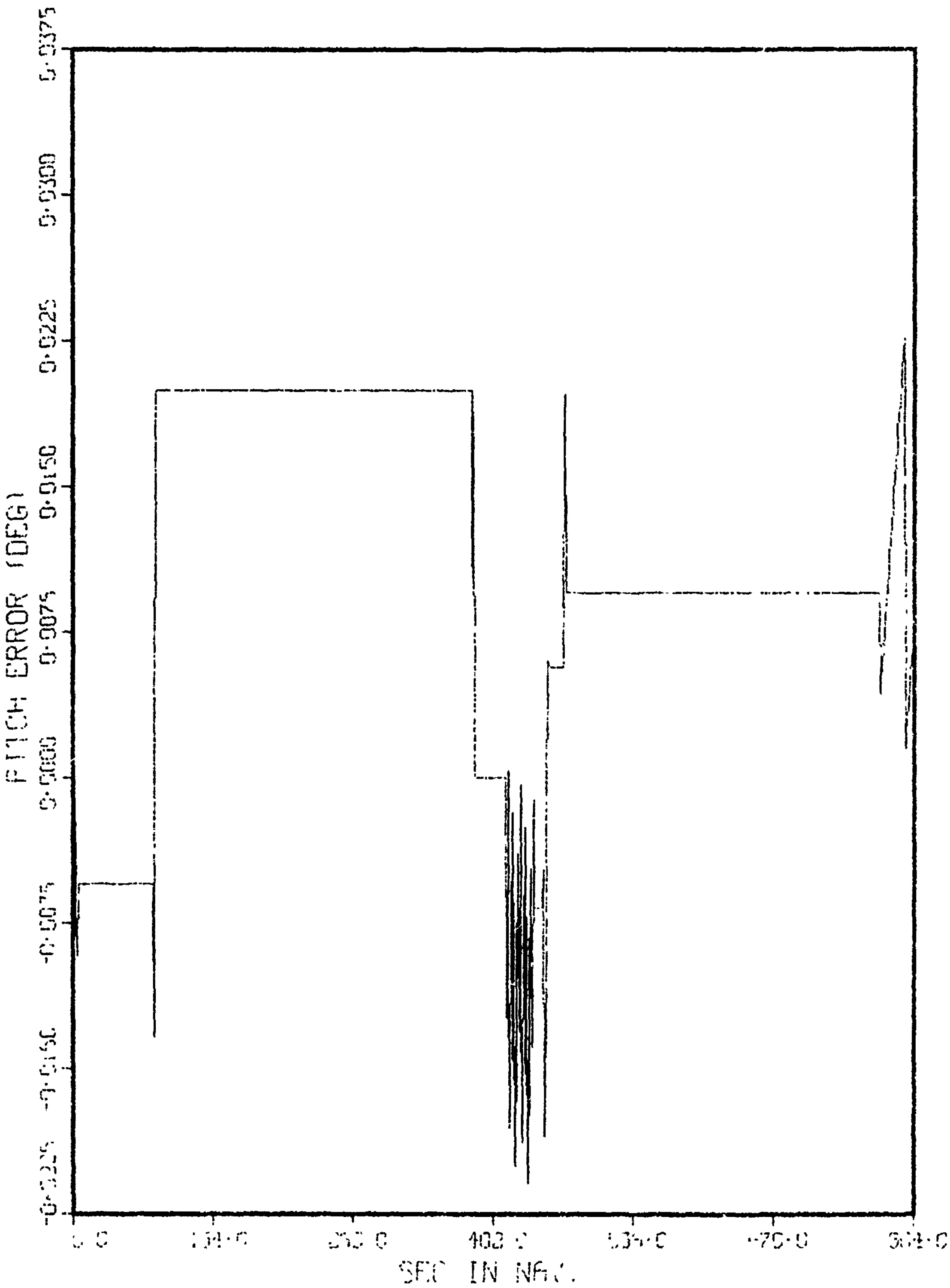
Plot #45



LONG F4 RUN BASE S/W SEQ 16
ROLL ERROR (DEG)
0·0370
0·0296
0·0222
0·0148
0·0074
0·0000
-0·0074
-0·0148
-0·0222
0·0
134·0
268·0
402·0
536·0
670·0
804·0
SEC IN NAV.

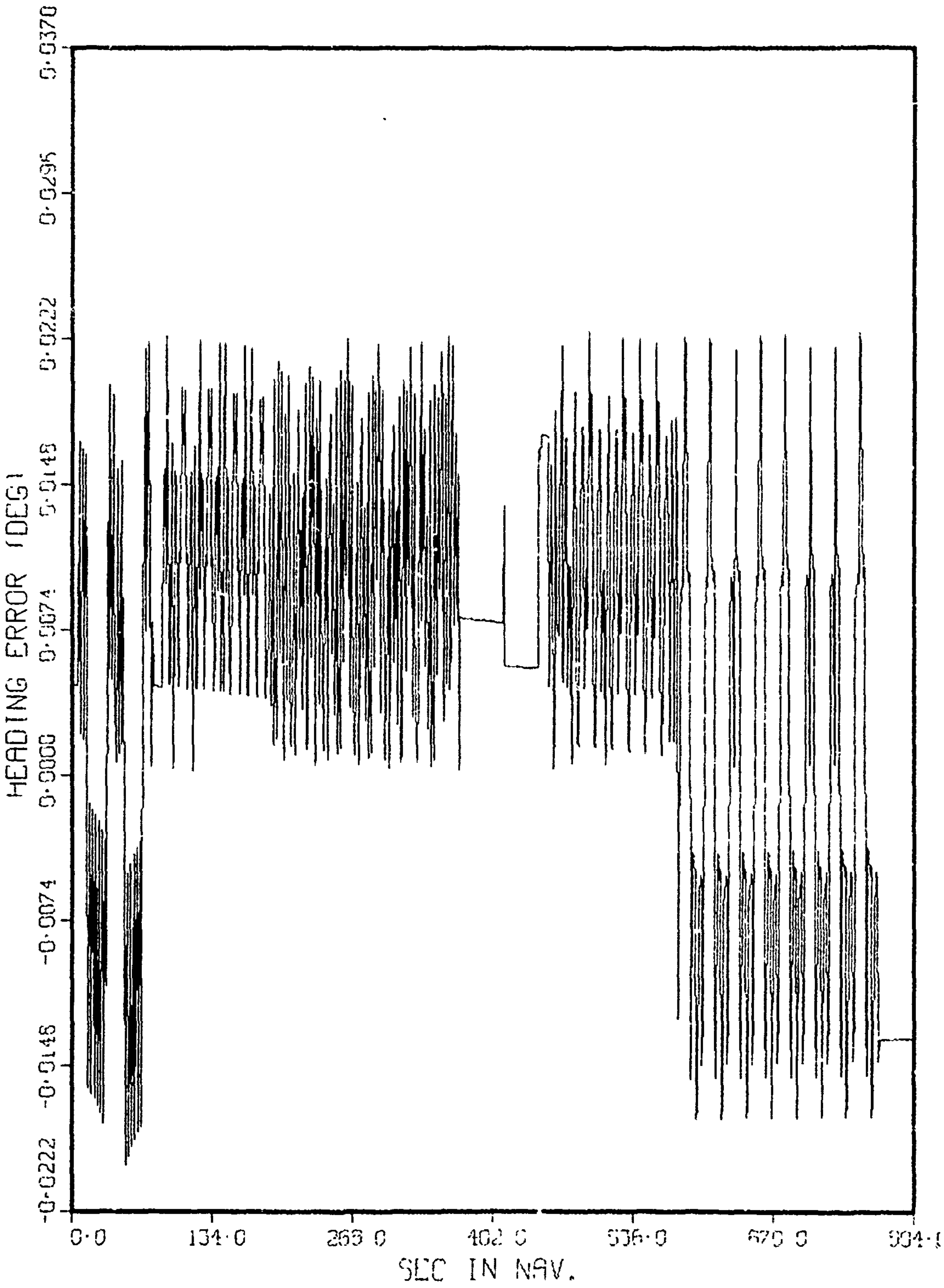
Plot #46

LONG F4 RUN BASE S/W SEQ 16



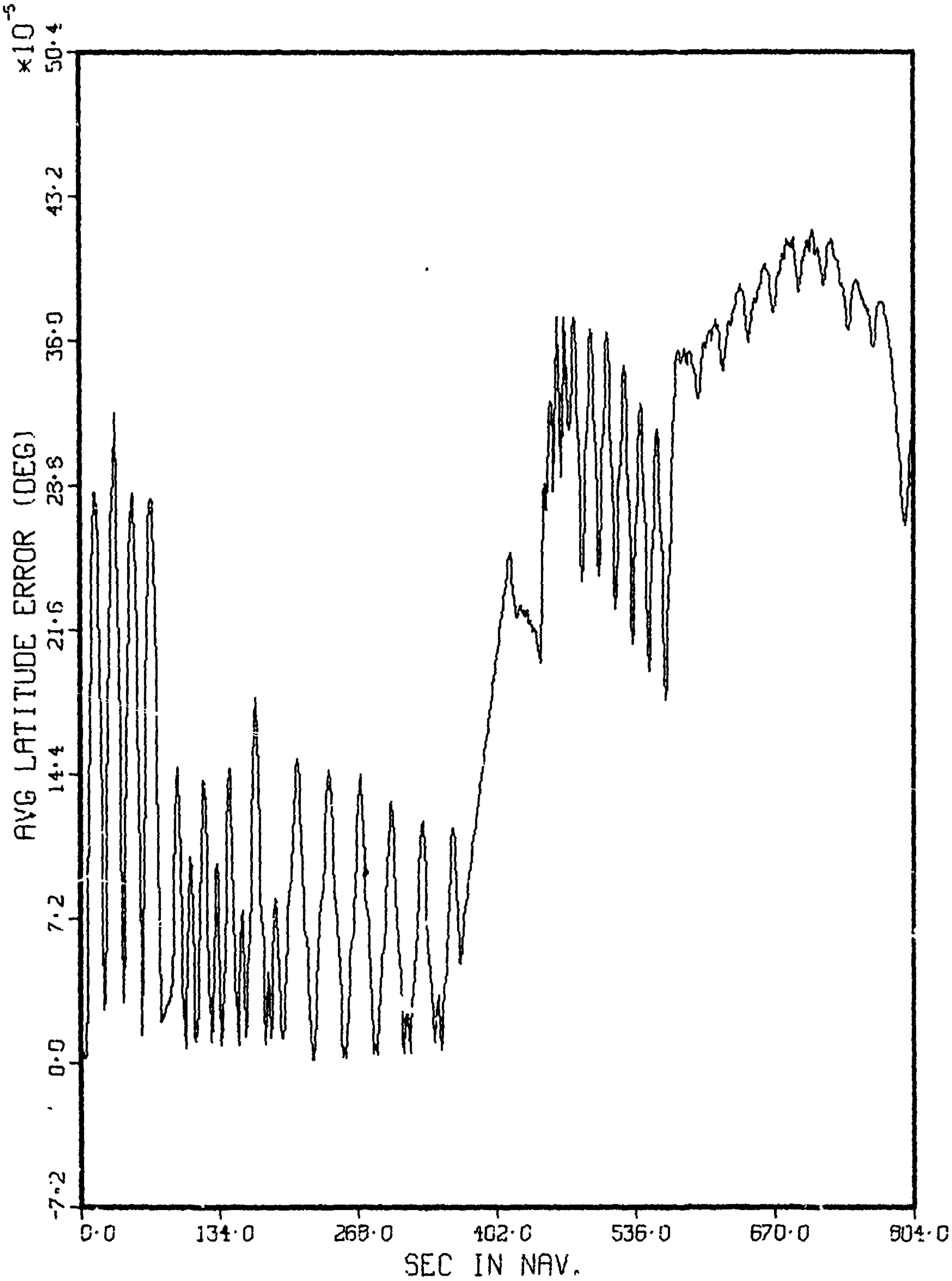
Plot #47

LONG F4 RUN BASE S/W SEQ 16



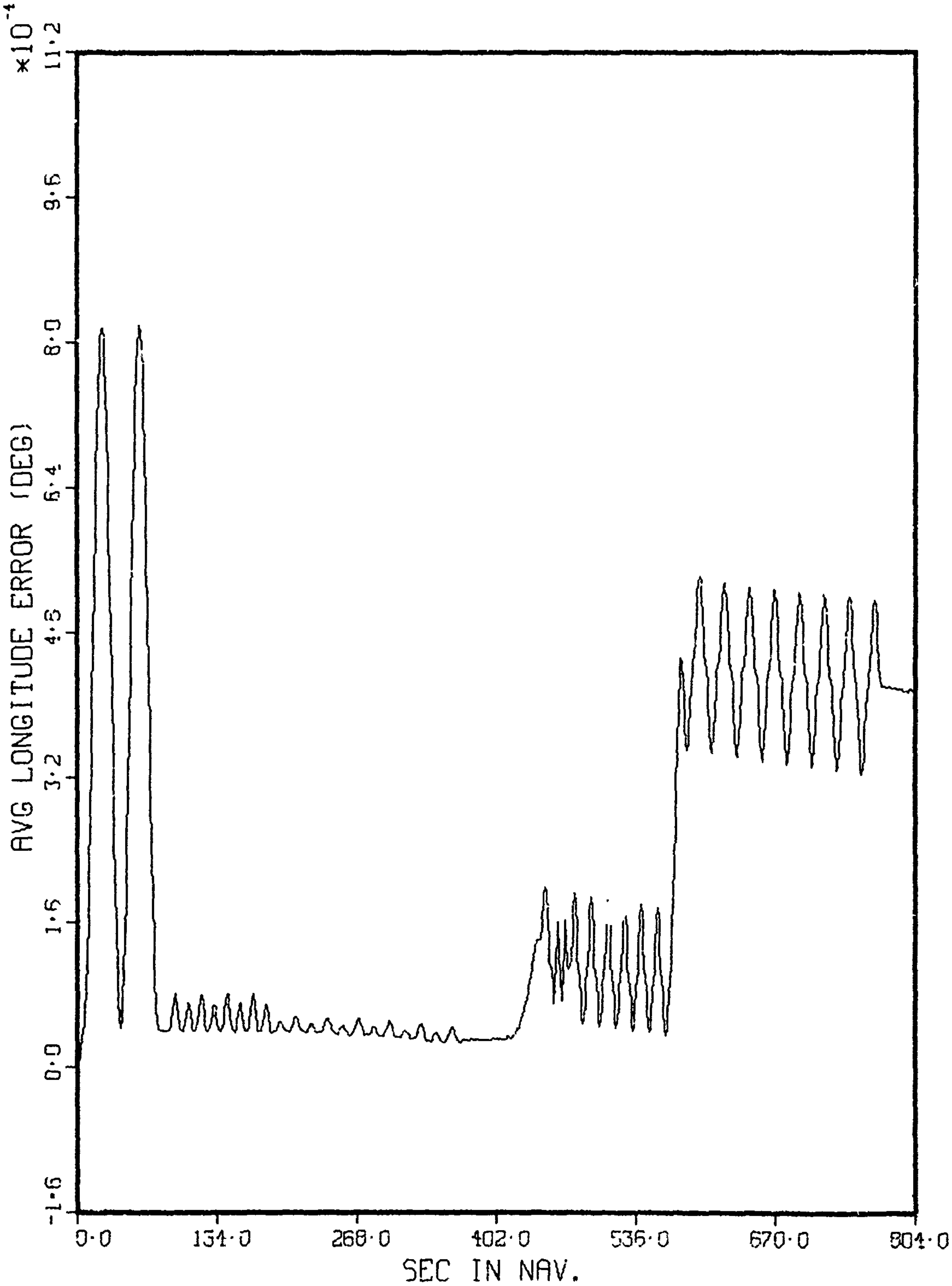
Plot #48

LONG F4 RUN BASE S/W SEQ 16

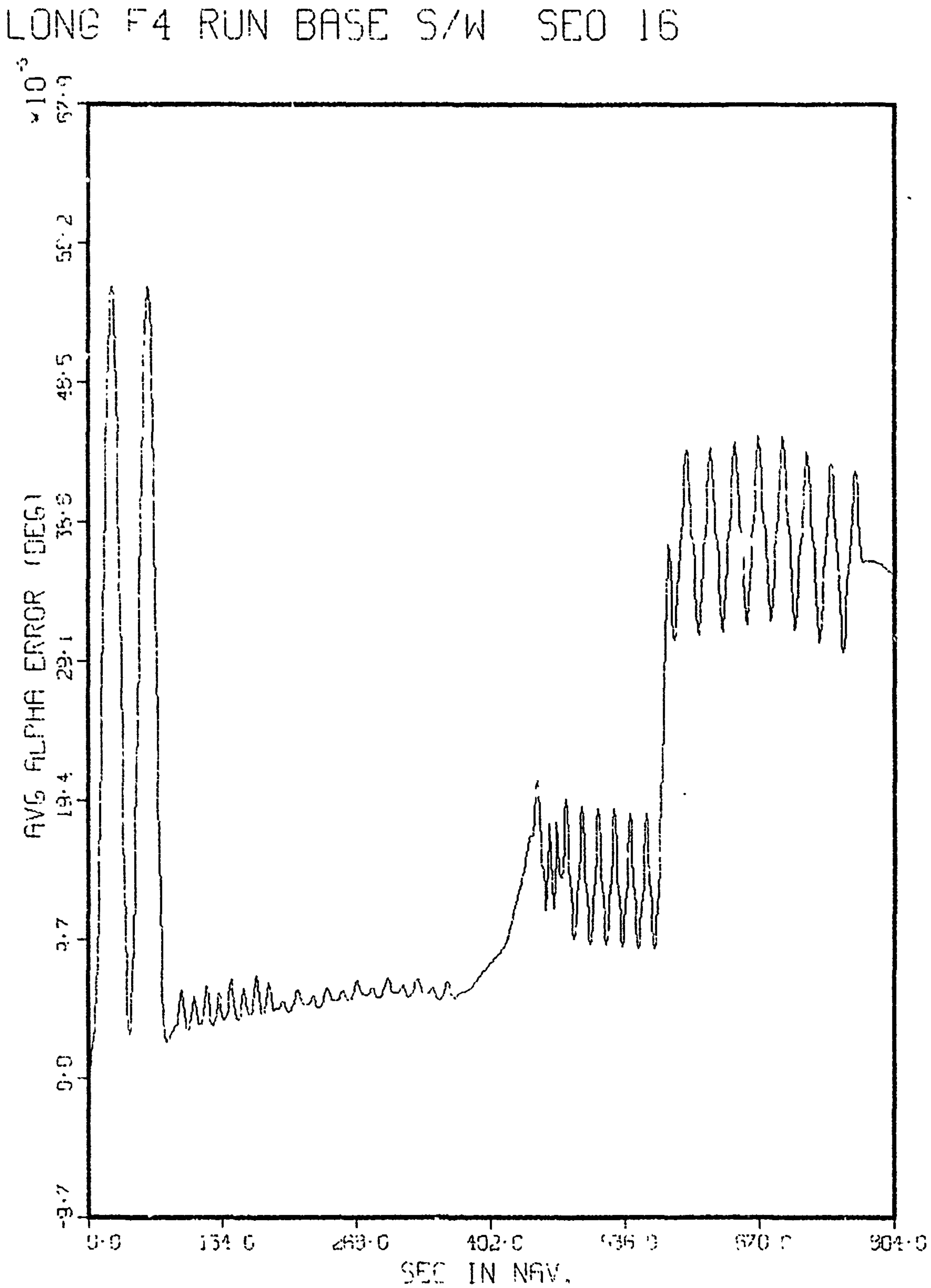


Plot #9

LONG F4 RUN BASE S/W SEQ 16



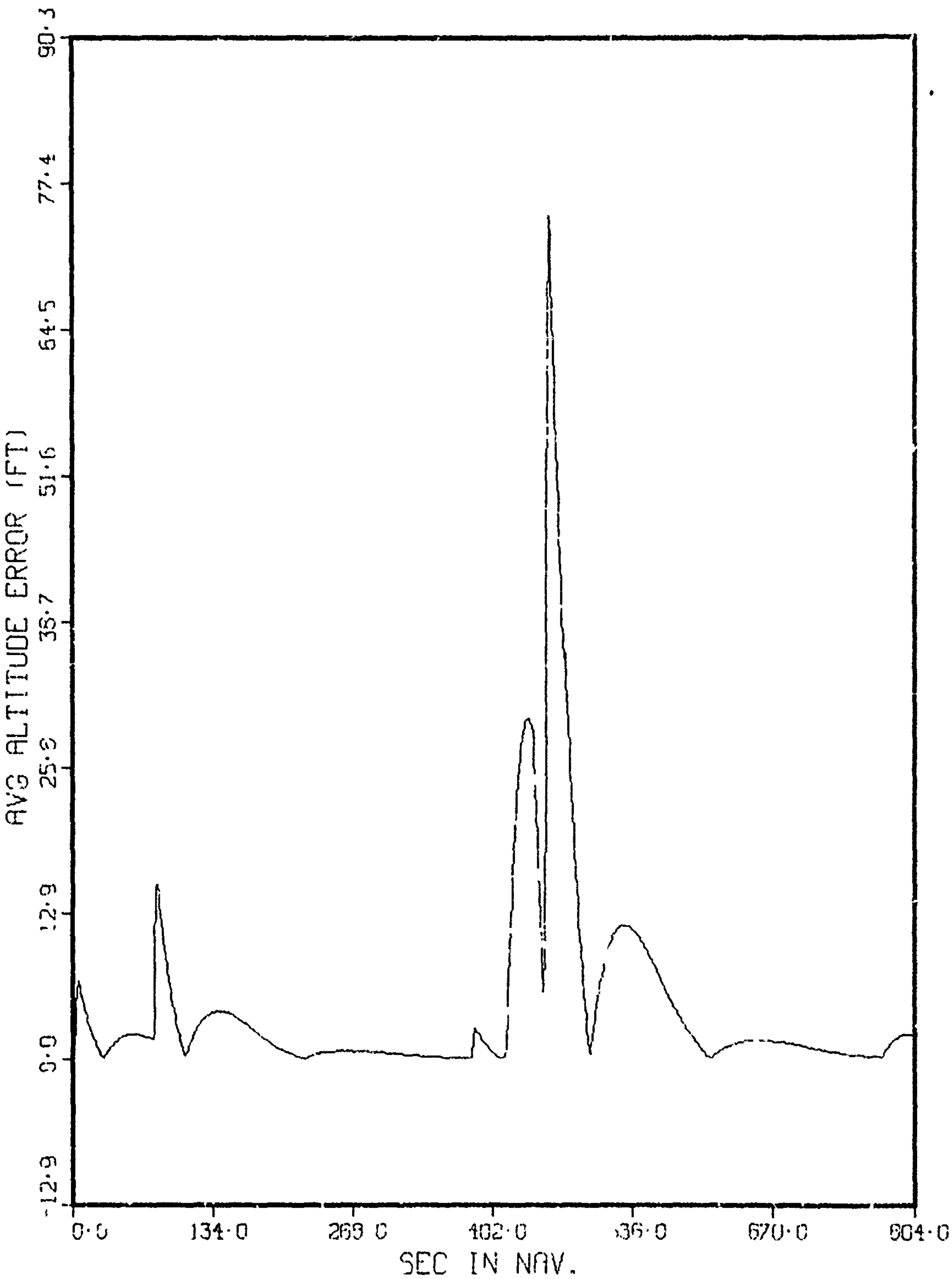
Plot #50



LONG F4 RUN BASE S/W SEQ 16
$\times 10^{-3}$
AVG ALPHA ERROR (DEG)
SEC IN NAV.

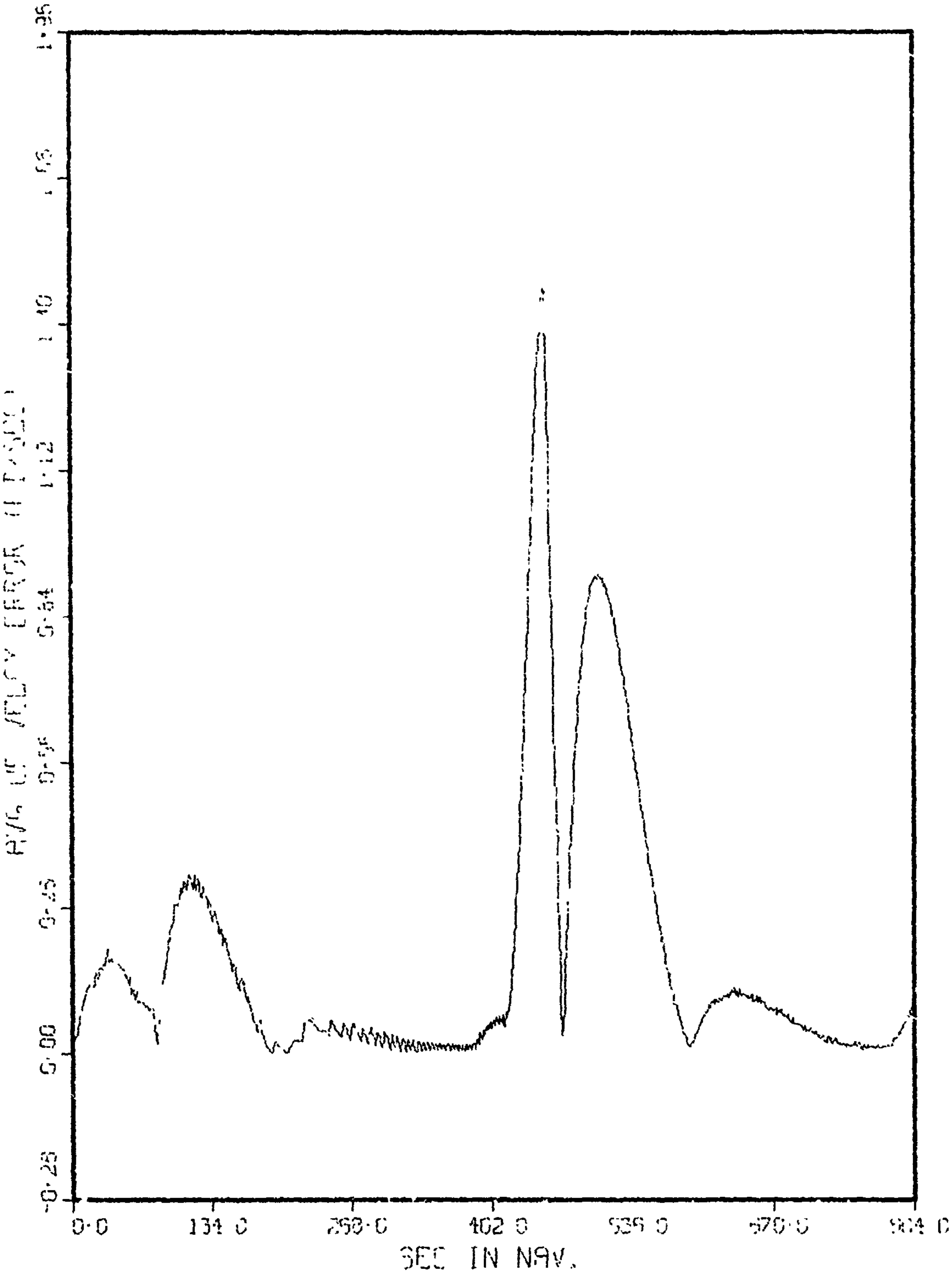
Plot #51

LONG F4 RUN BASE S/W SEQ 16



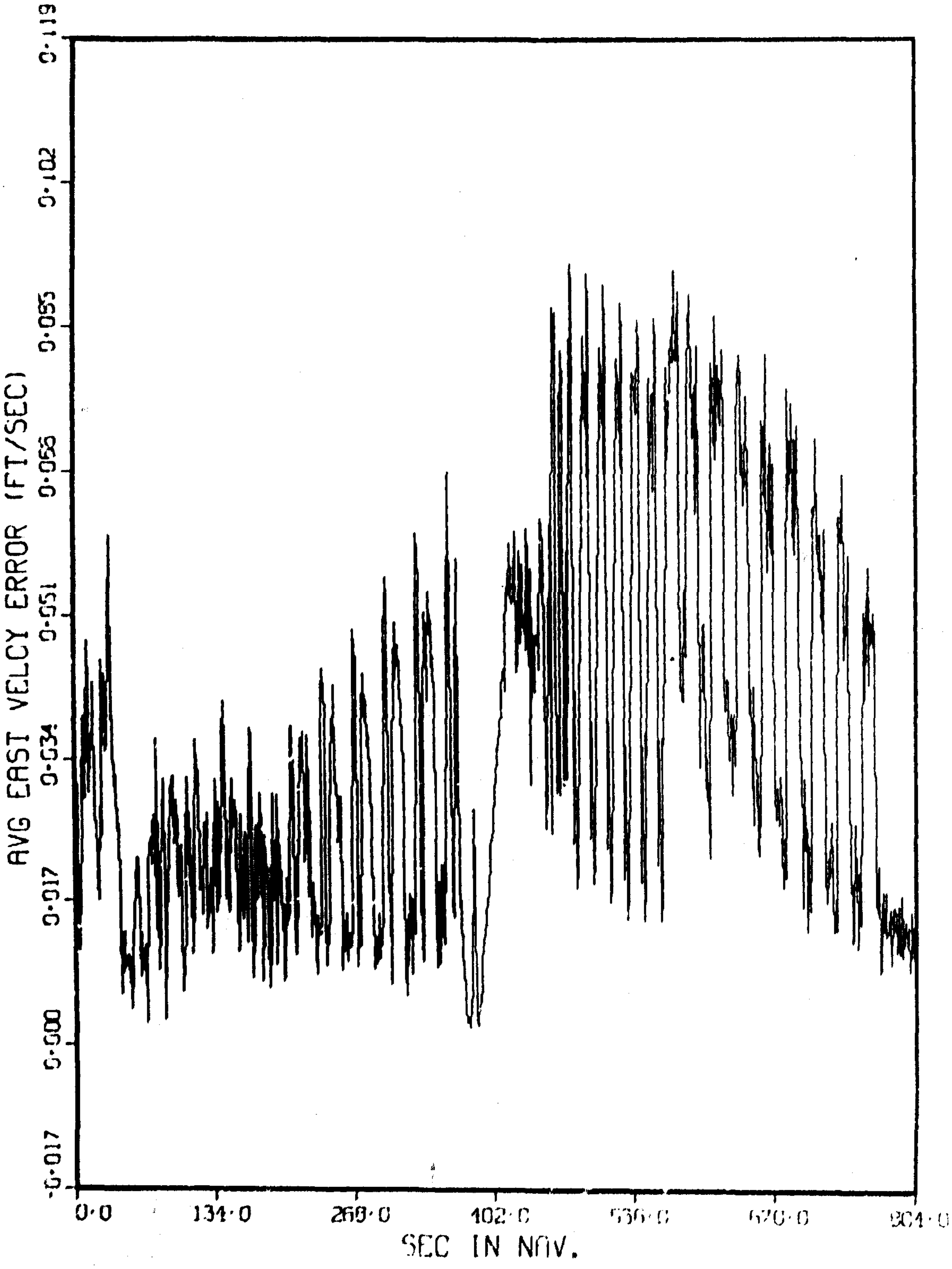
Plot #52

LONG F4 RUN BASE S/W SEQ 16



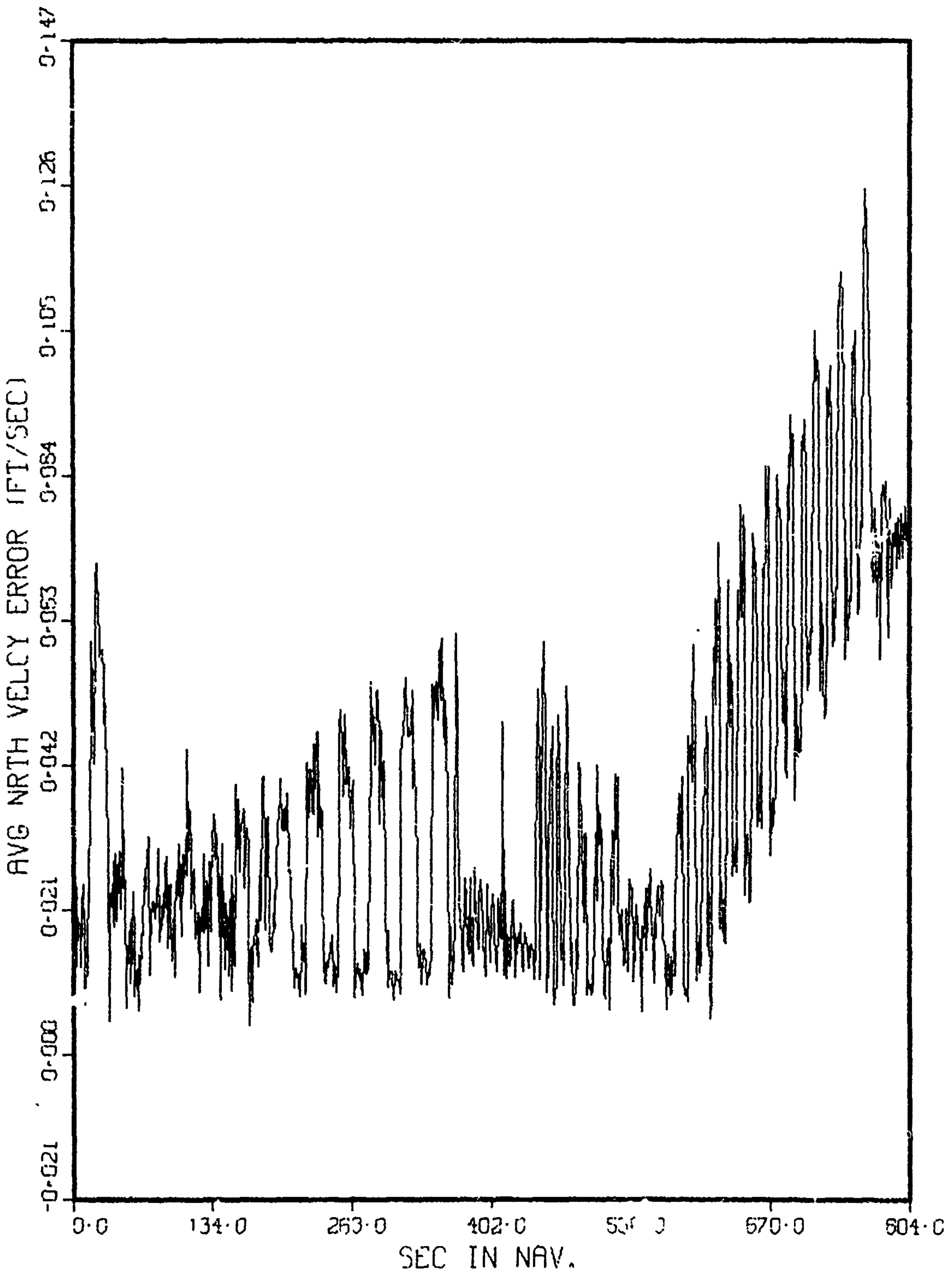
Plot #53

LONG F4 RUN BASE S/W SEQ 16



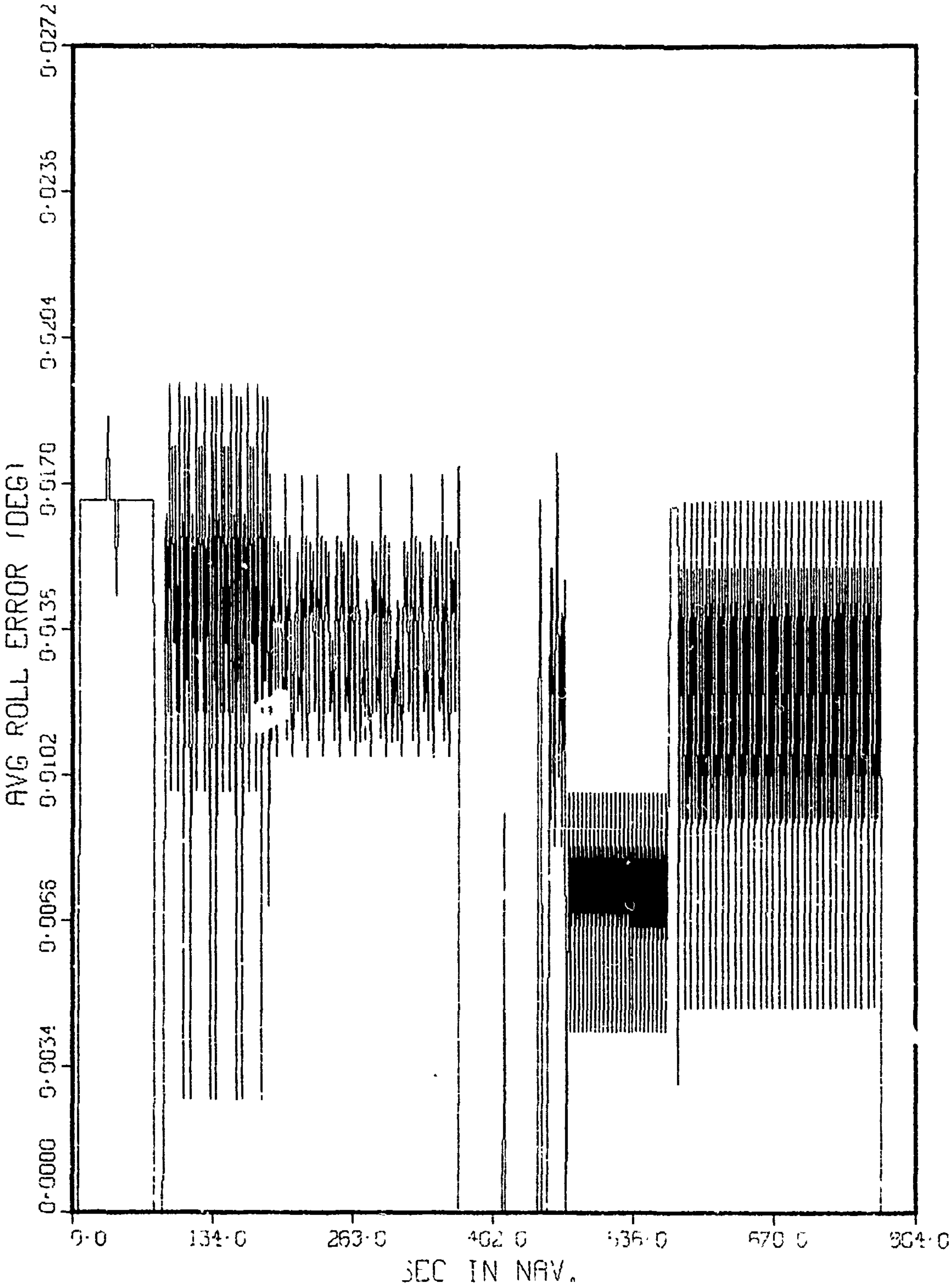
Plot #54

LONG F4 RUN BASE S/W SEQ 16



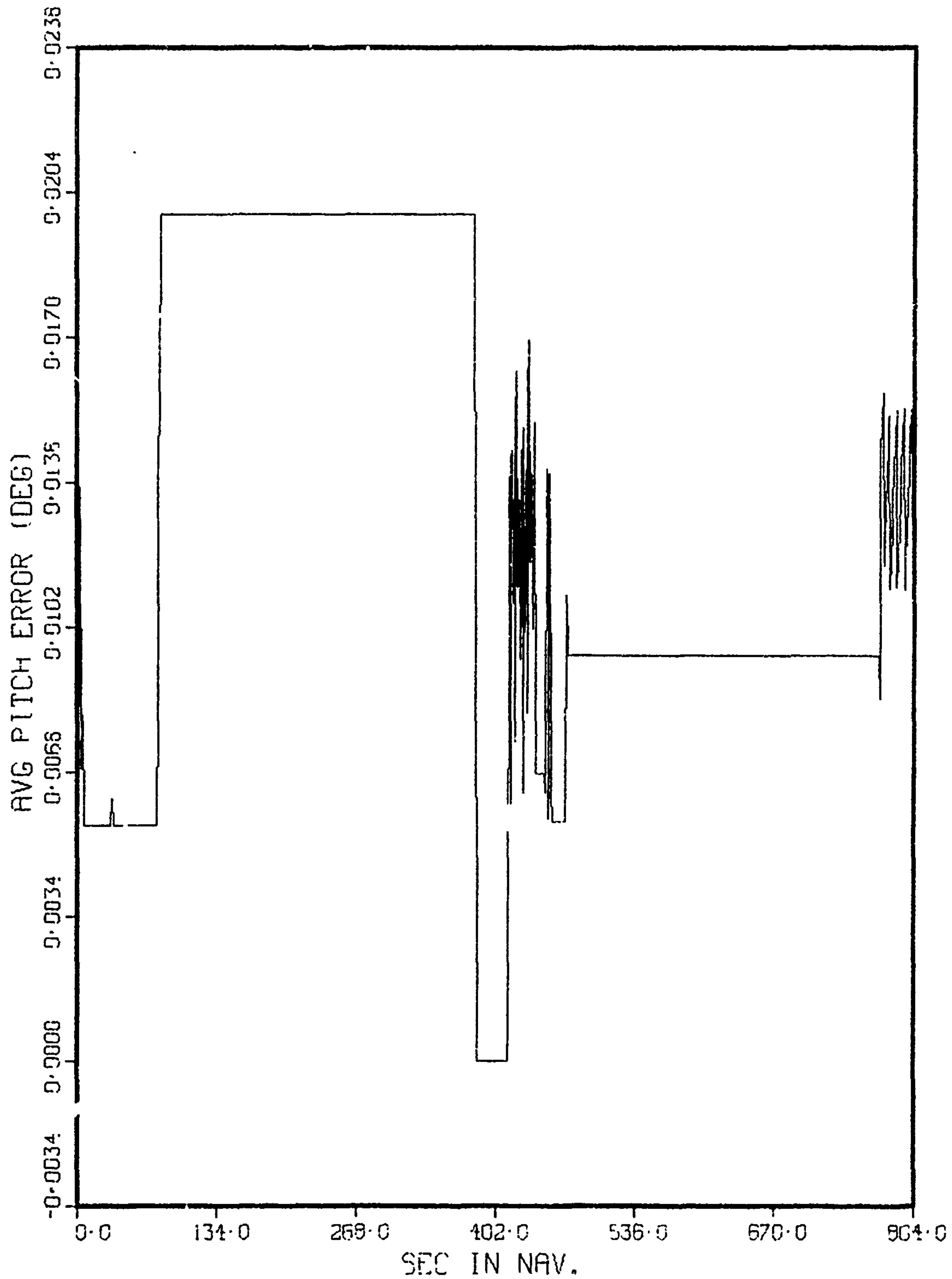
Plot #55

LONG F4 RUN BASE S/W SEQ 16

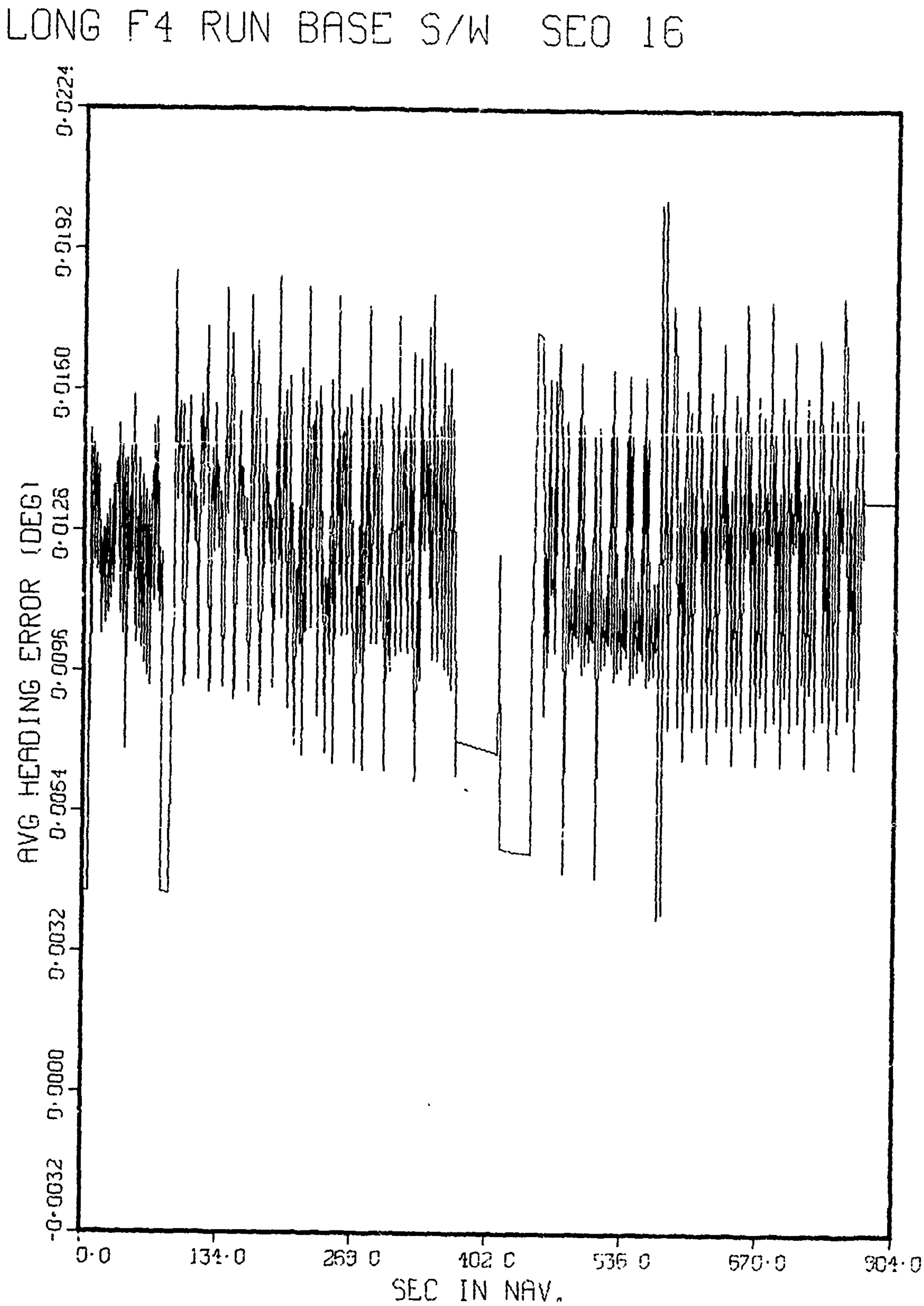


Plot #56

LONG F4 RUN BASE S/W SEQ 16

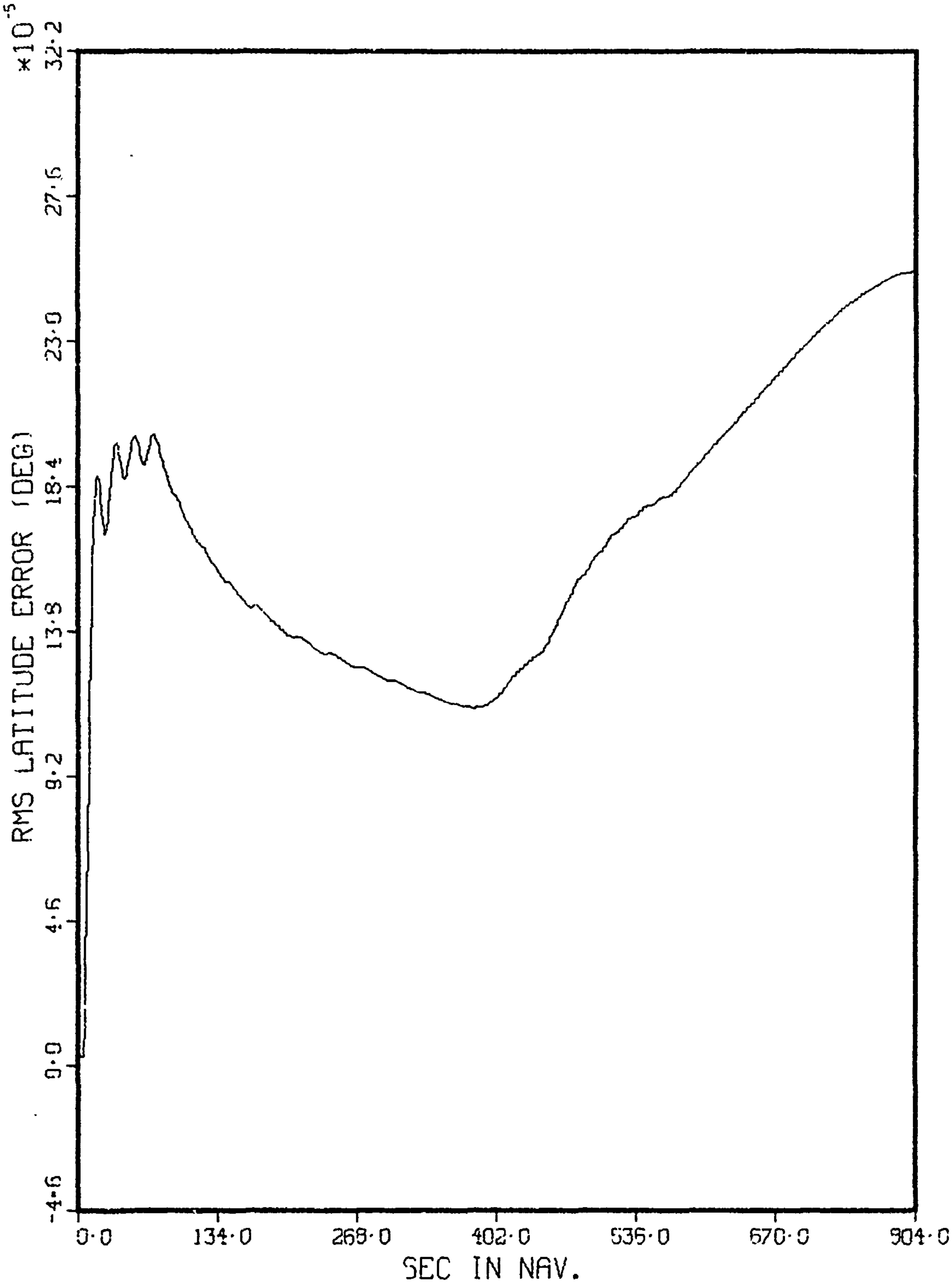


Plot #57


LONG F4 RUN BASE S/W SEQ 16
AVG HEADING ERROR (DEG)
0.0224
0.0192
0.0160
0.0128
0.0096
0.0064
0.0032
0.0000
-0.0032
0.0
134.0
268.0
402.0
536.0
670.0
804.0
SEC IN NAV.

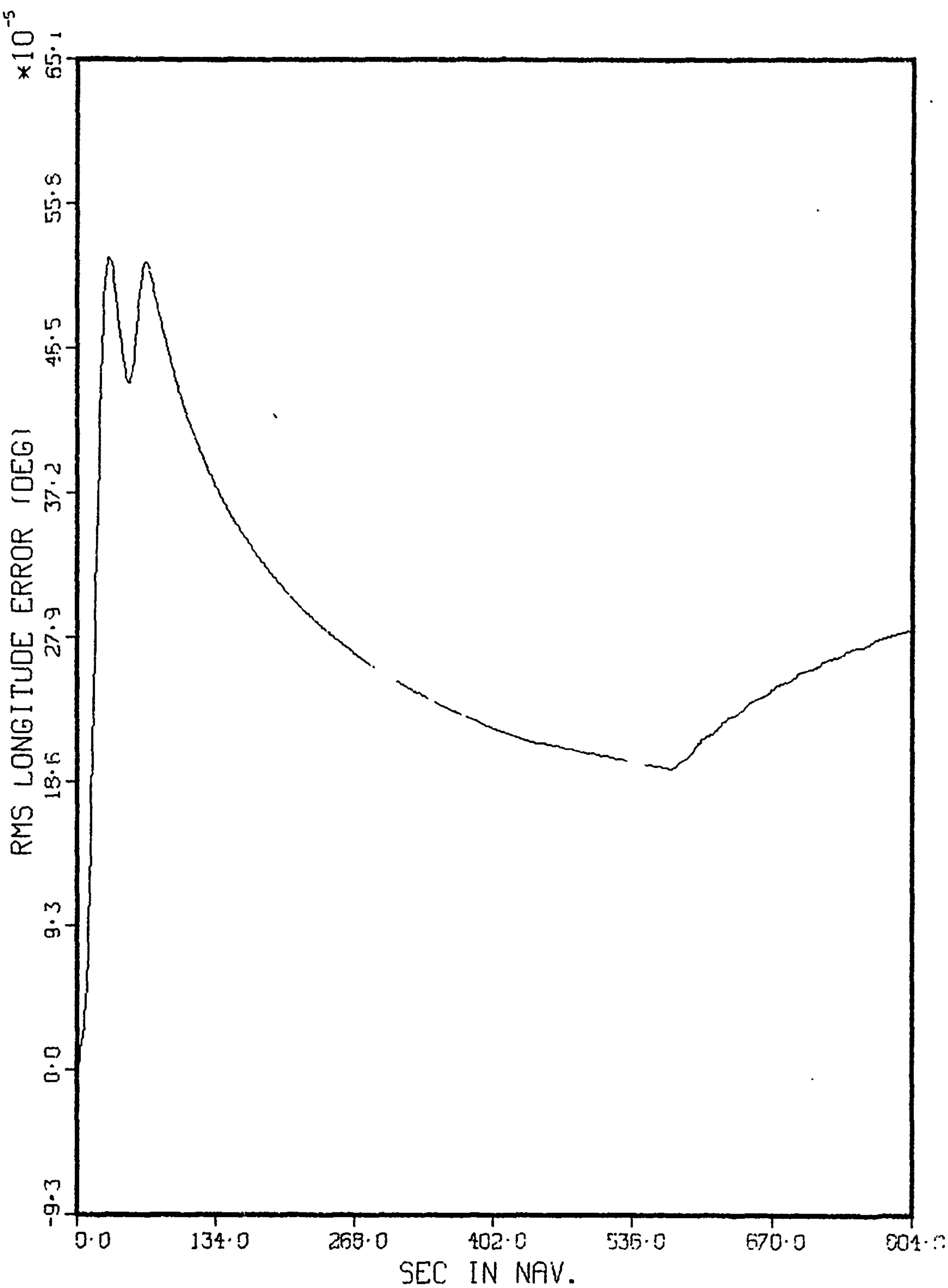
Plot #58

LONG F4 RUN BASE S/W SEQ 16



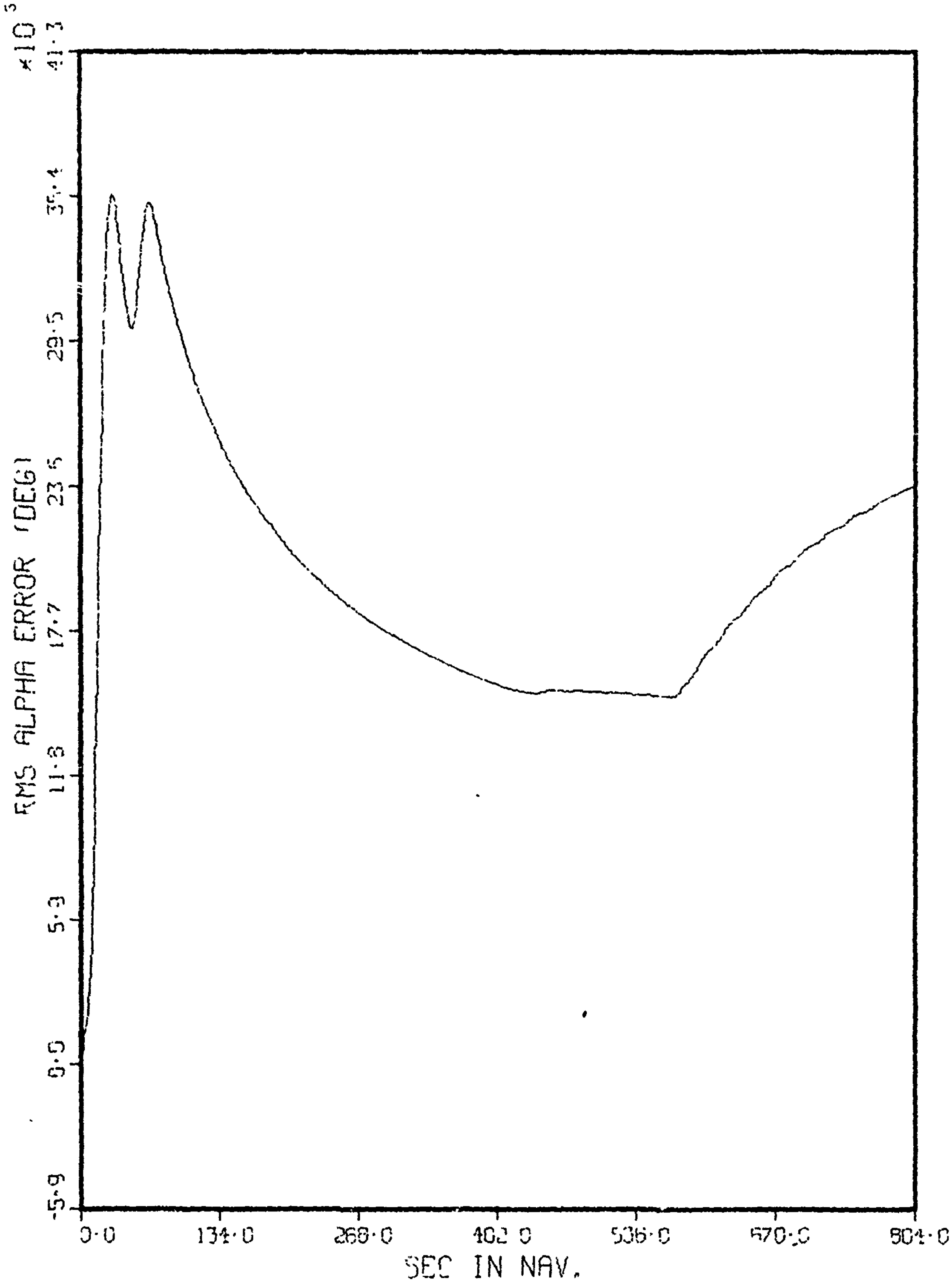
Plot #59

LONG F4 RUN BASE S/W SEQ 16



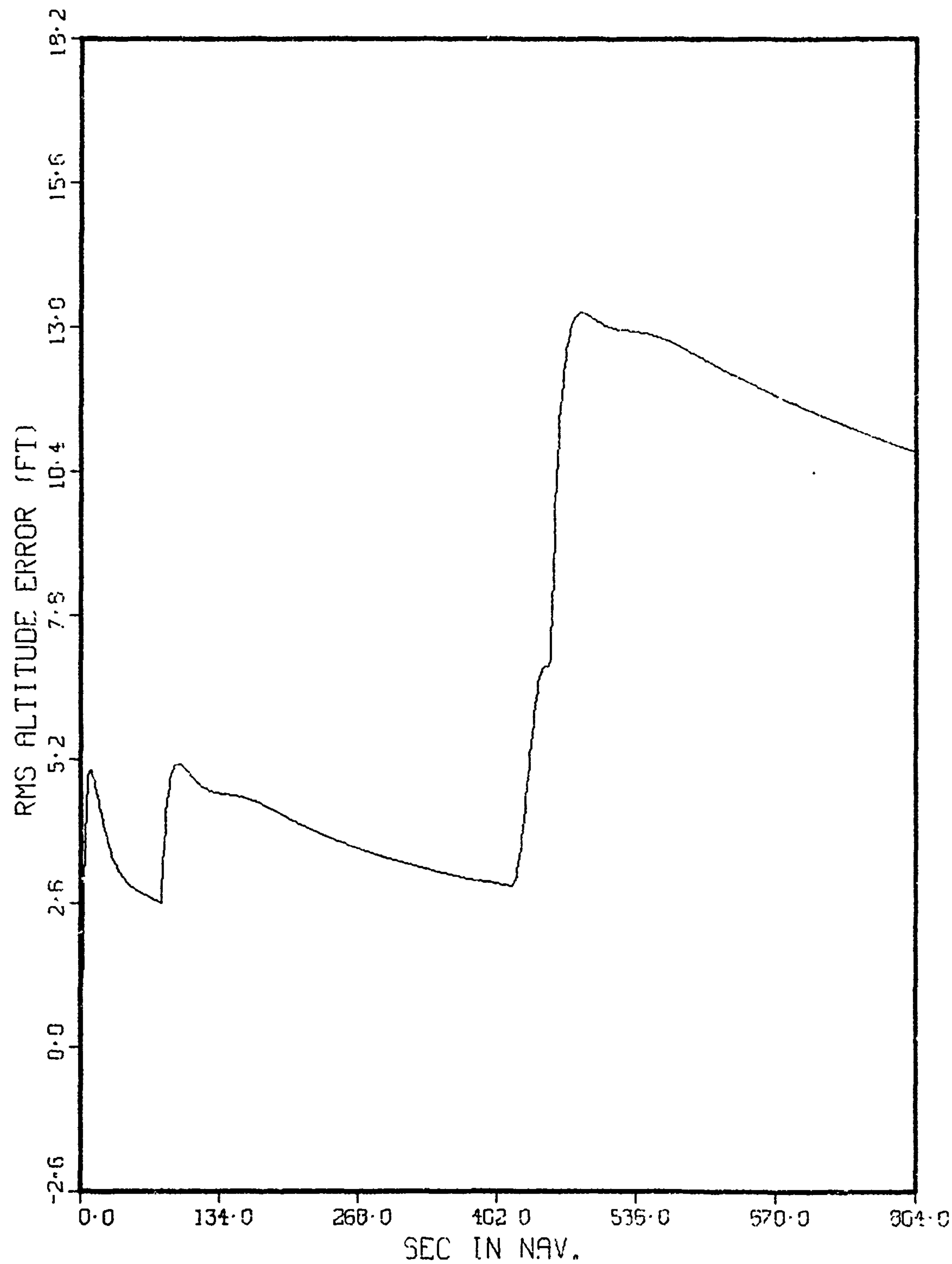
Plot #60

LONG F4 RUN BASE S/W SEQ 16



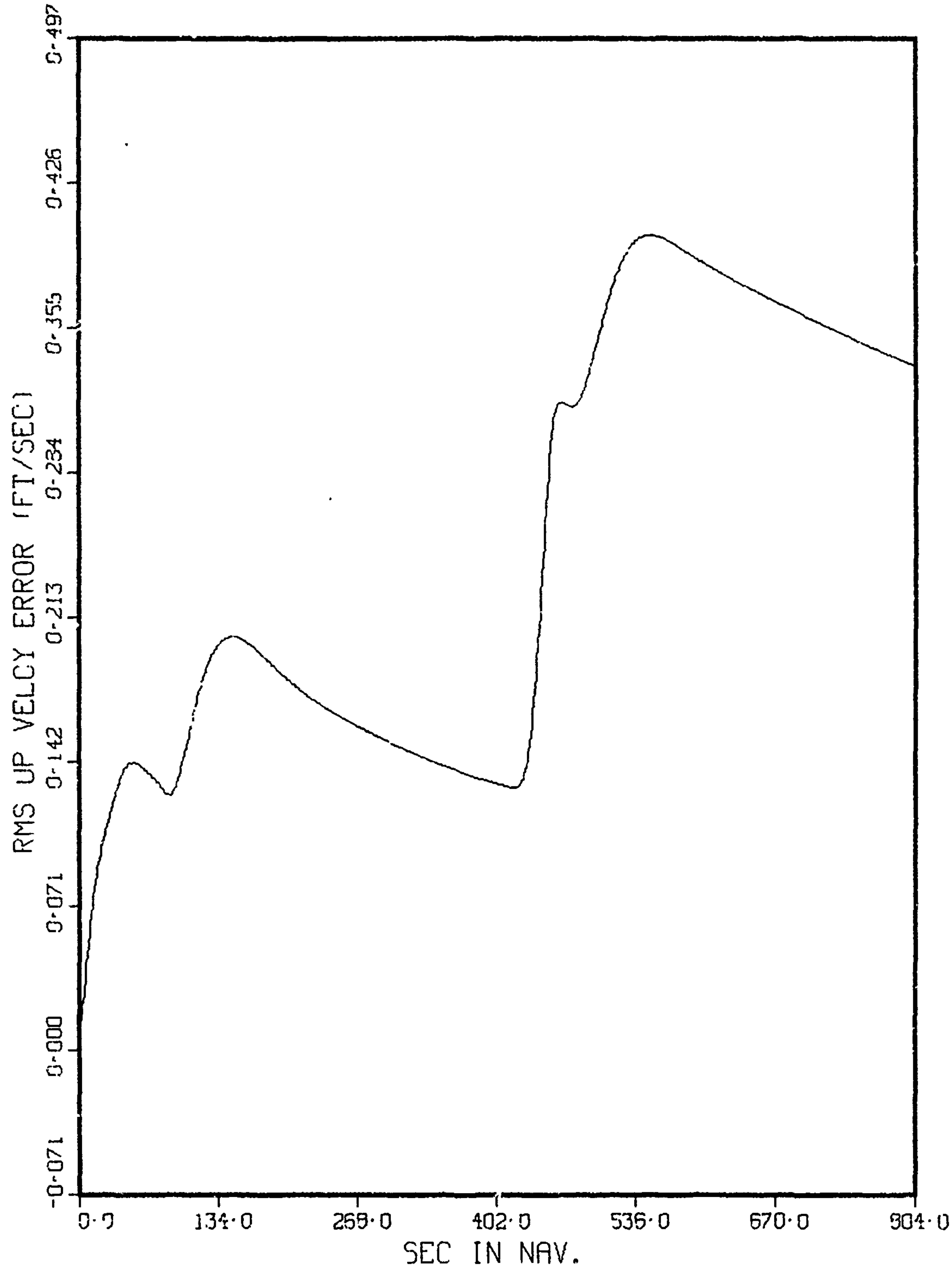
Plot #51

LONG F4 RUN BASE S/W SEQ 16

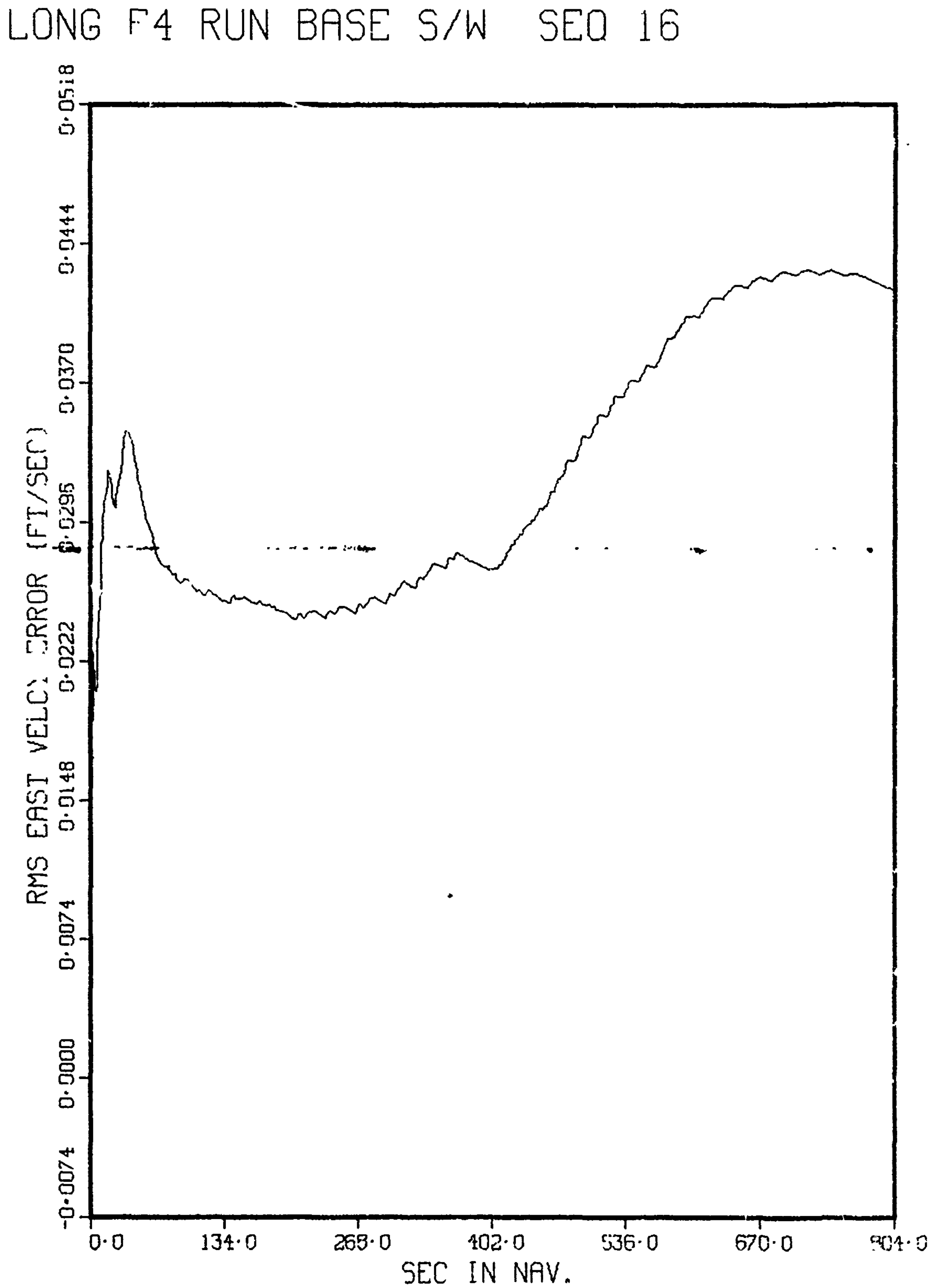


Plot #62

LONG F4 RUN BASE S/W SEQ 16

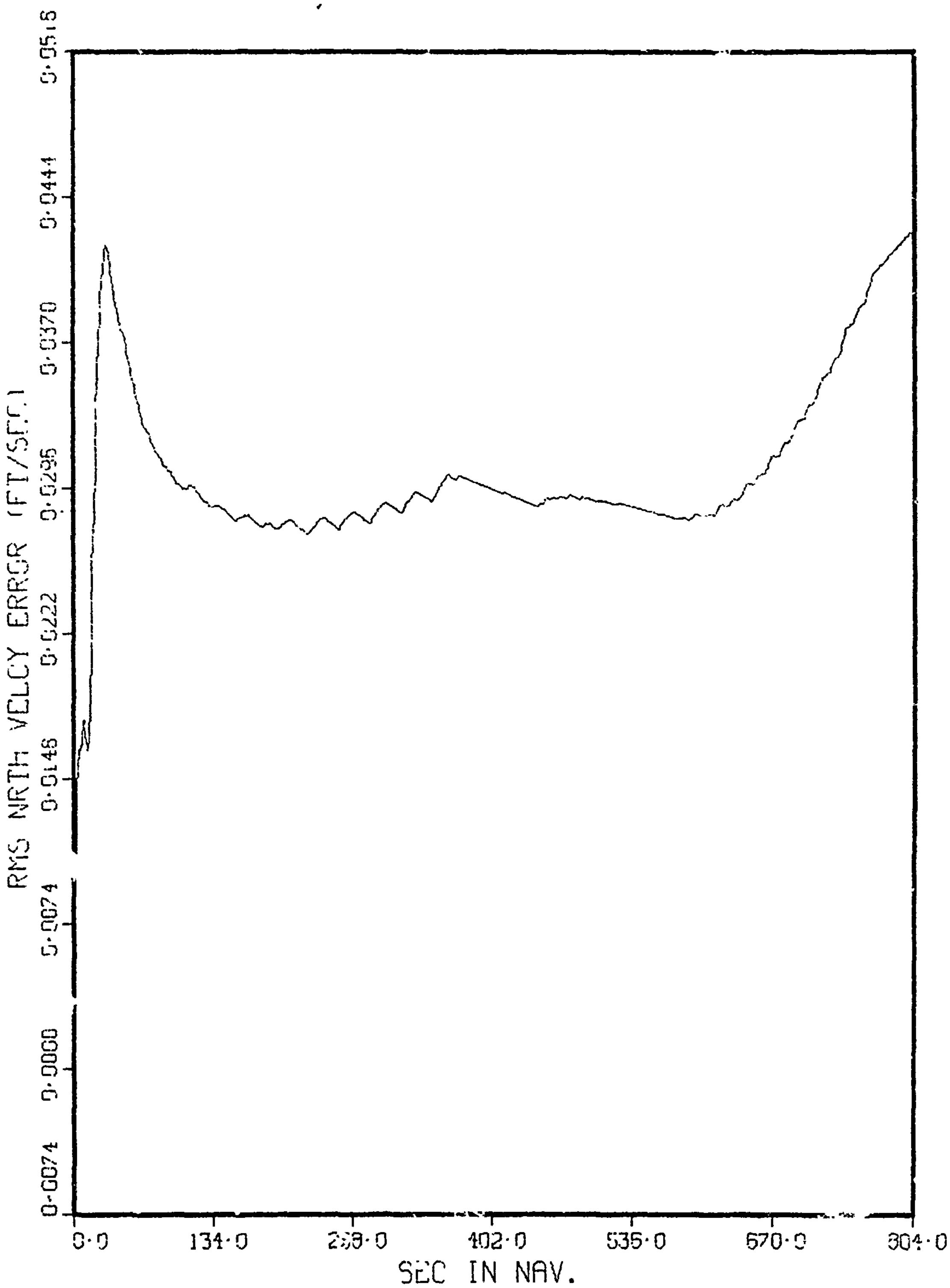


Plot #63

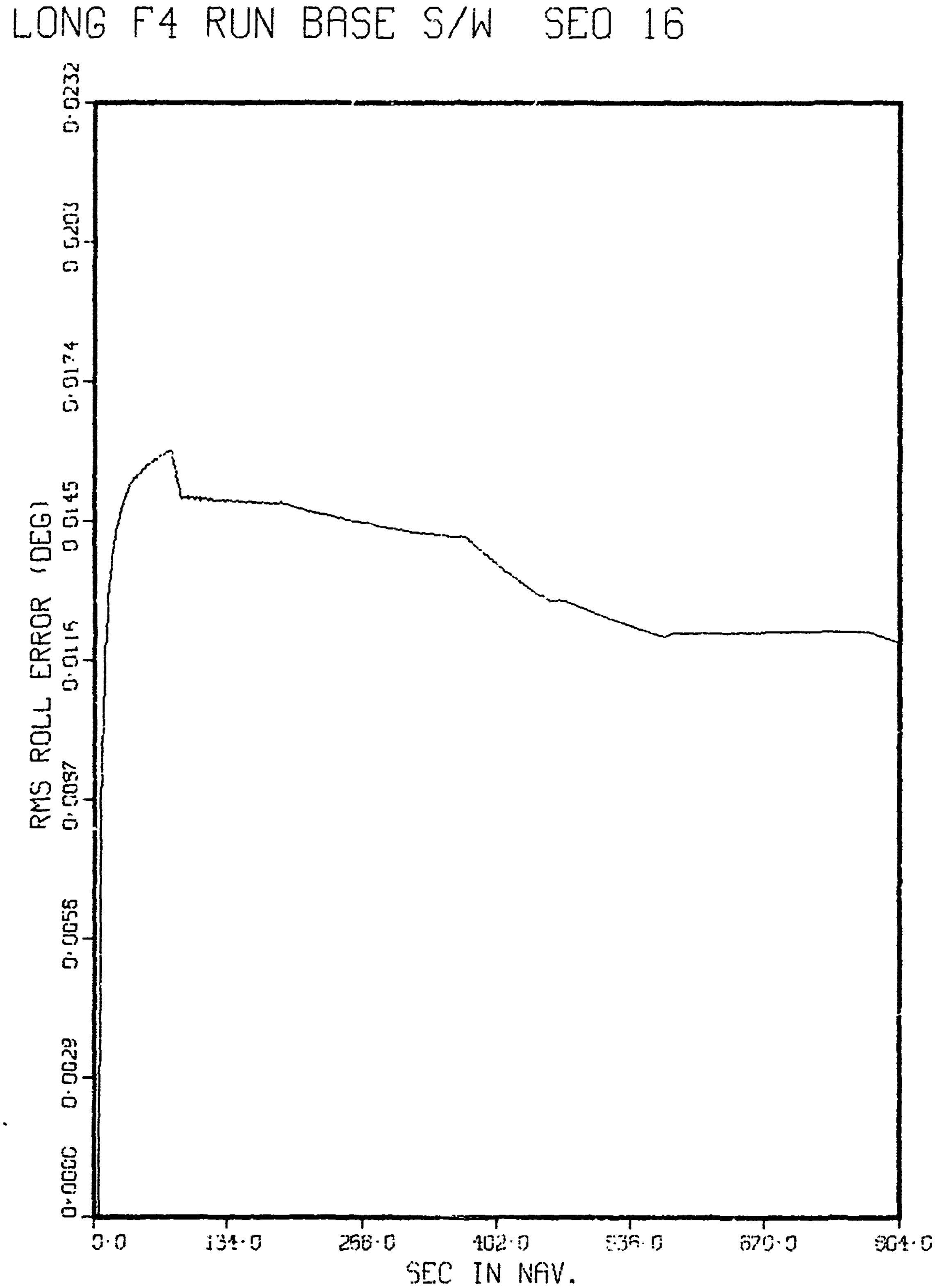

LONG F4 RUN BASE S/W SEQ 16
RMS EAST VELCY ERROR (FT/SEC)
0.0518
0.0444
0.0370
0.0296
0.0222
0.0148
0.0074
0.0000
-0.0074
0.0
134.0
268.0
402.0
536.0
670.0
804.0
SEC IN NAV.

Plot #64

LONG F4 RUN BASE S/W SEQ 16



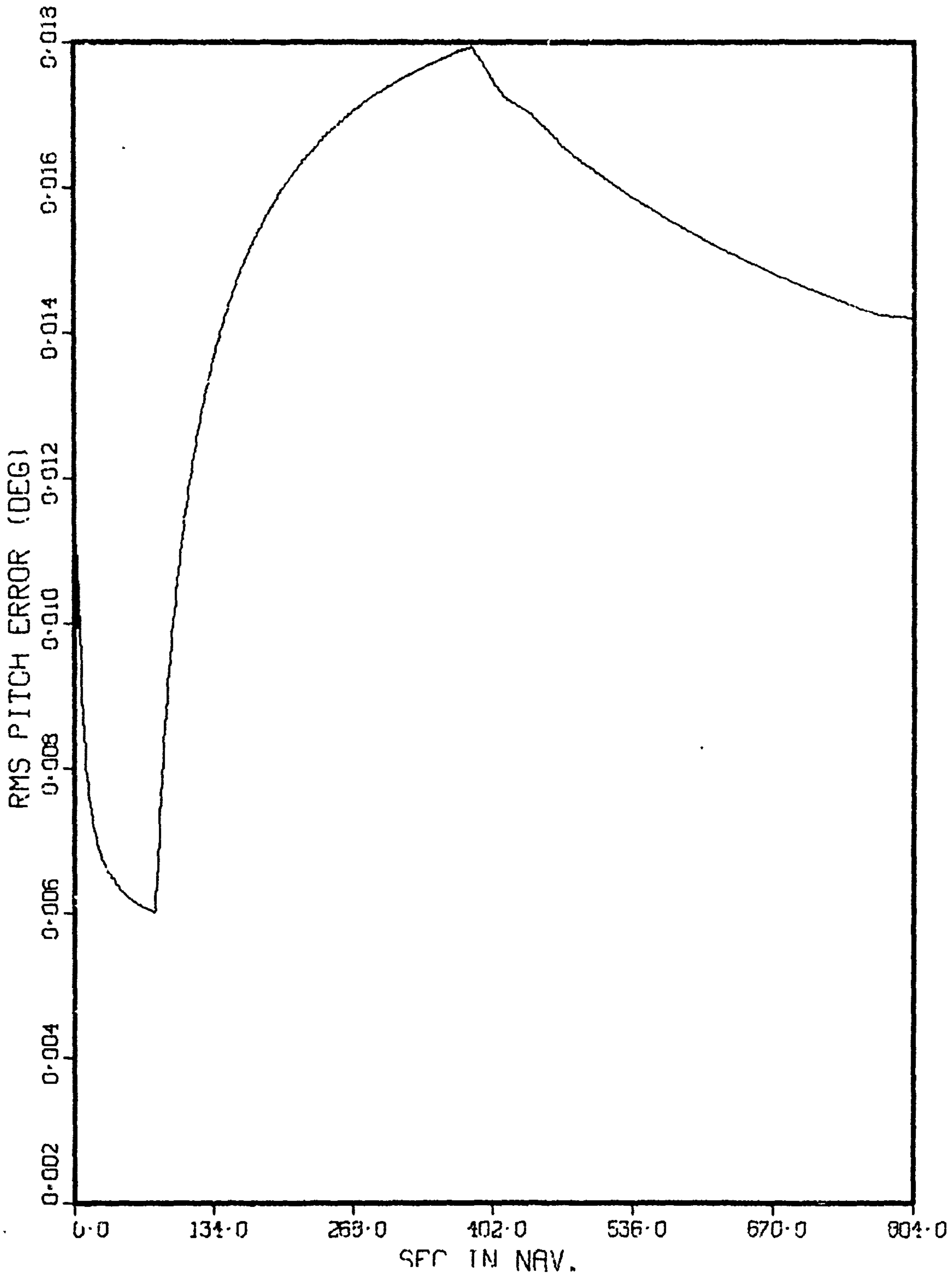
Plot #65



LONG F4 RUN BASE S/W SEQ 16
RMS ROLL ERROR (DEG)
0.0232
0.0203
0.0174
0.0145
0.0116
0.0087
0.0058
0.0029
0.0000
0.0
134.0
268.0
402.0
536.0
670.0
804.0
SEC IN NAV.

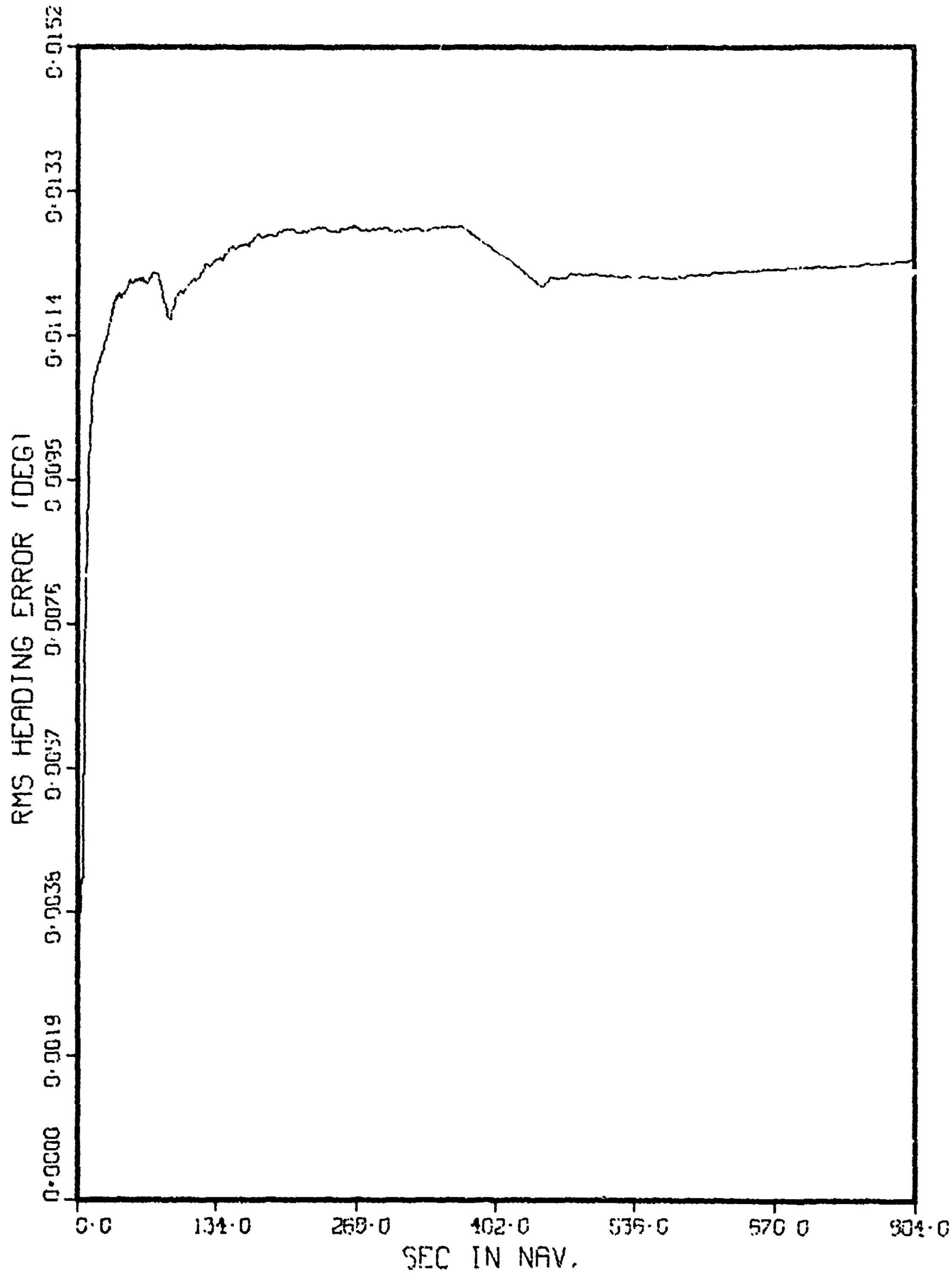
Plot #66

LONG F4 RUN BASE S/W SEQ 16



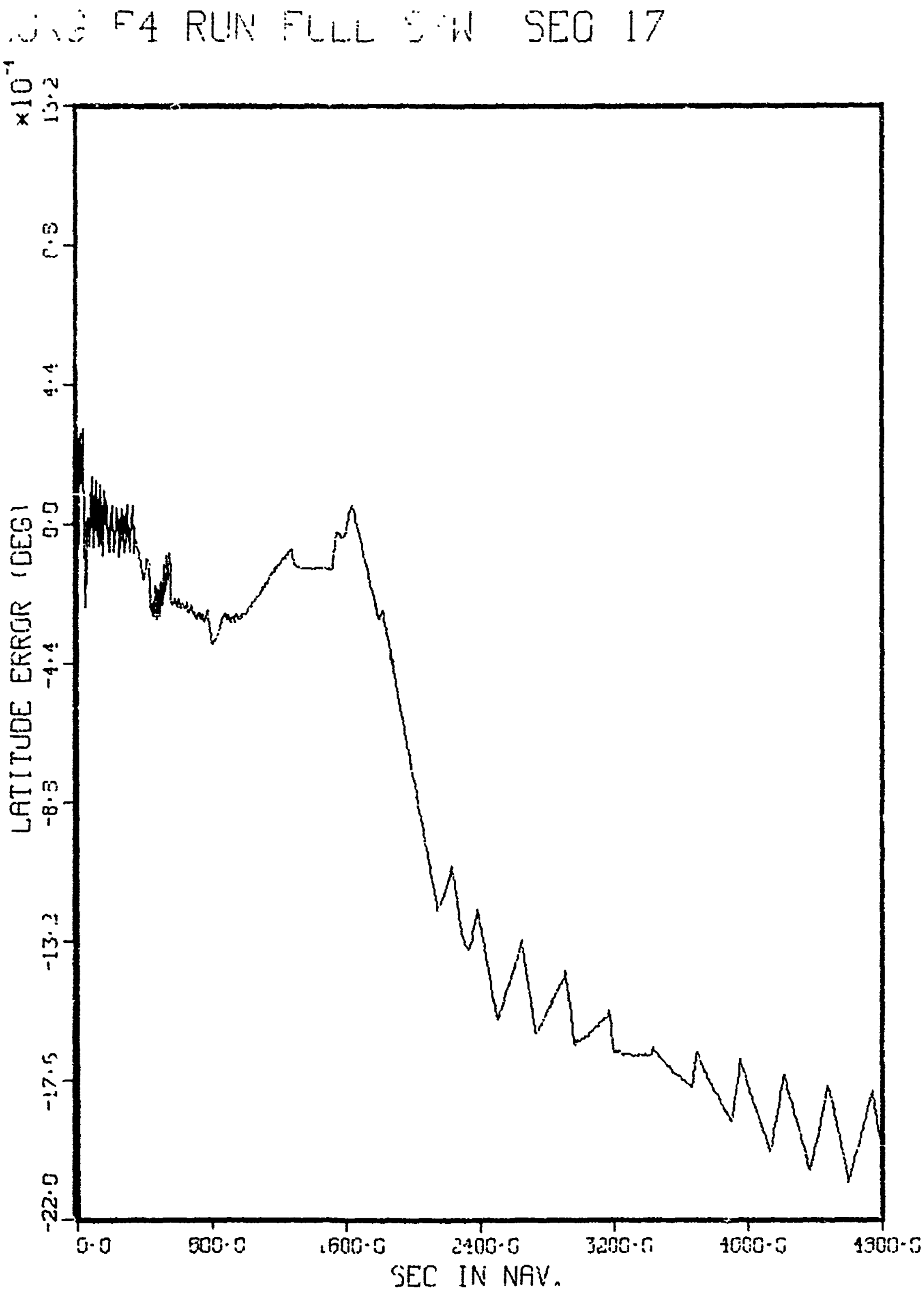
Plot#67

LONG F4 RUN BASE S/W SEQ 16



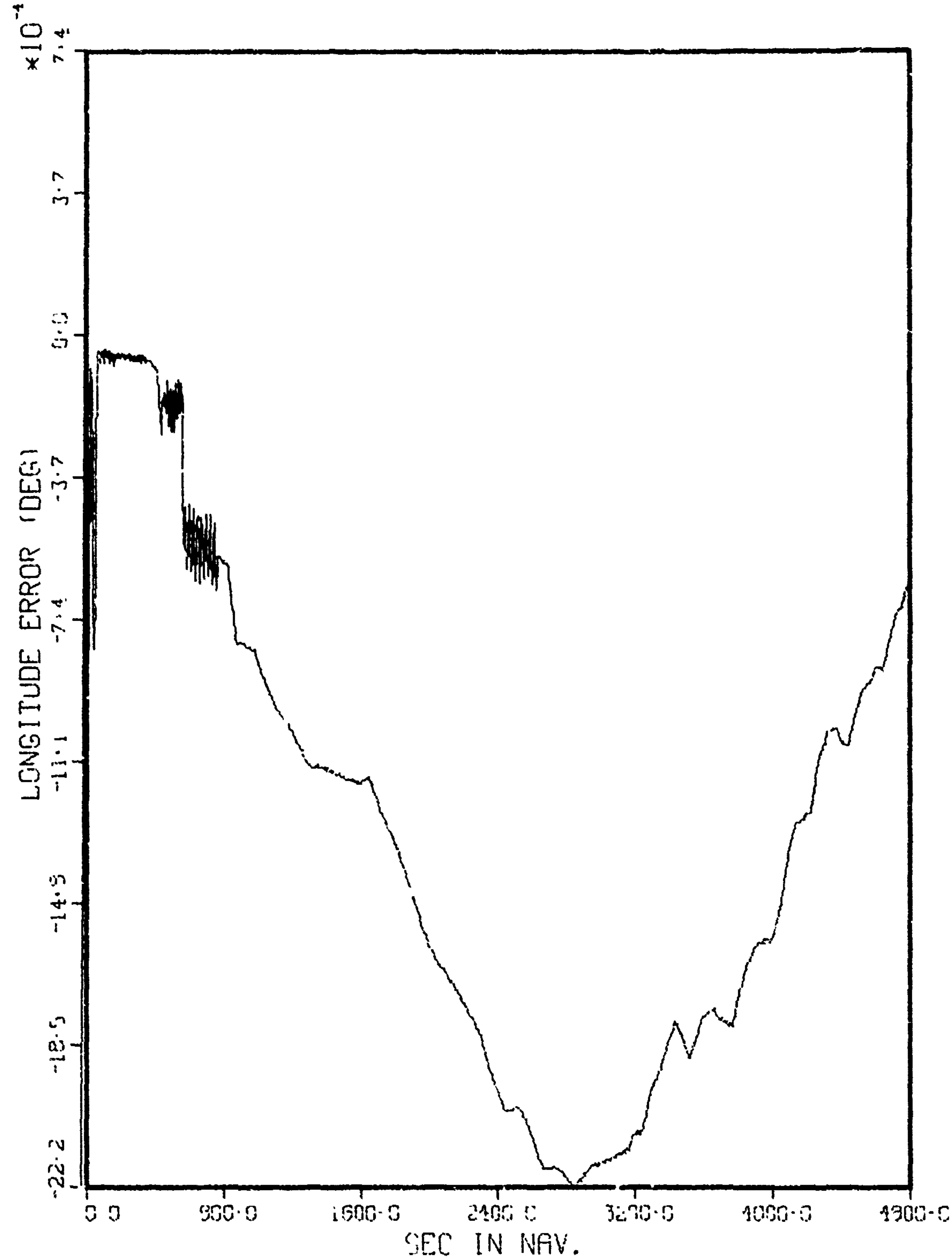
Plot #68

Δ between Base & Full



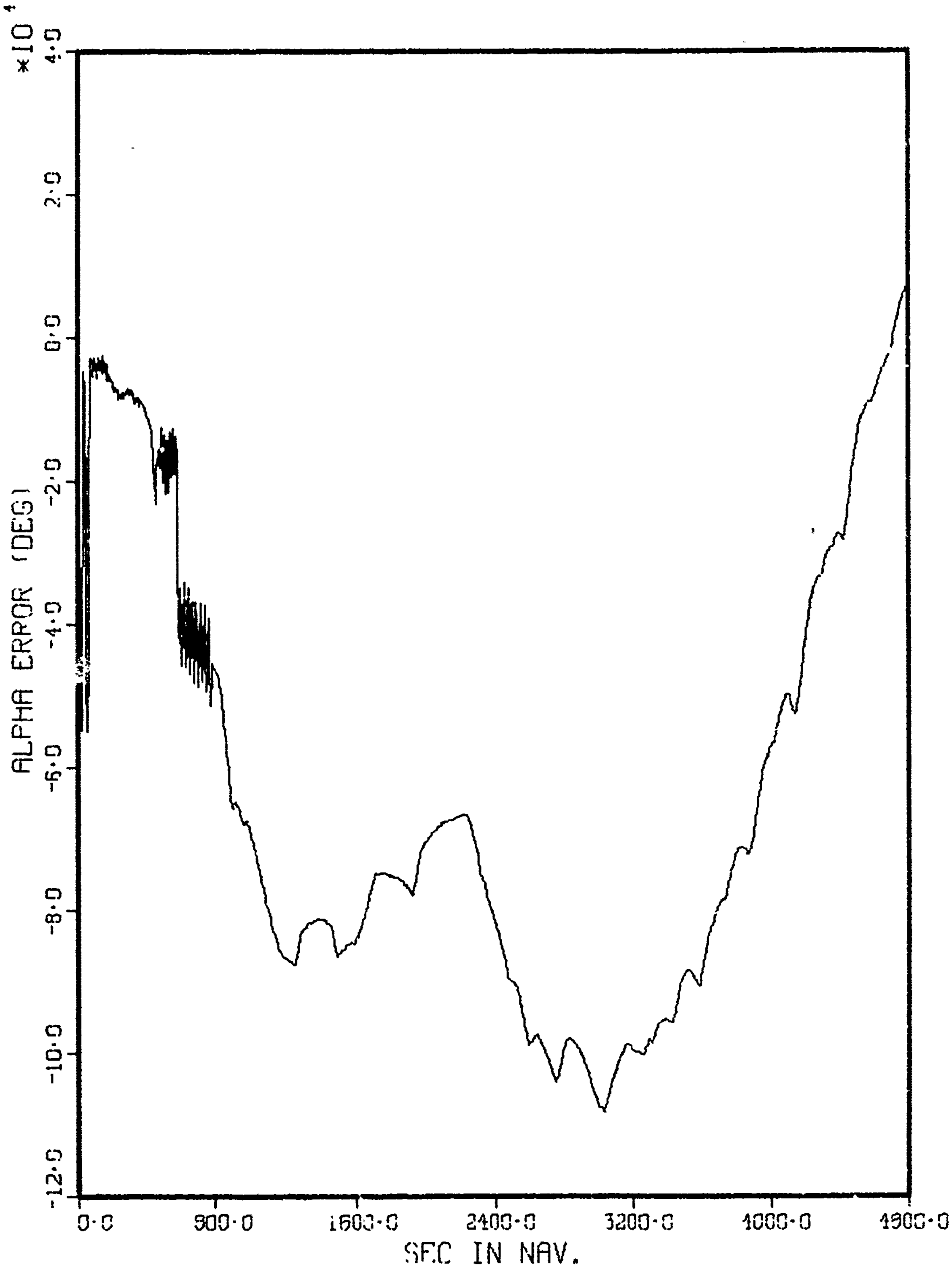
Δ between Base & Full   Plot #69

LONG F4 RUN FULL S/W SEQ 17



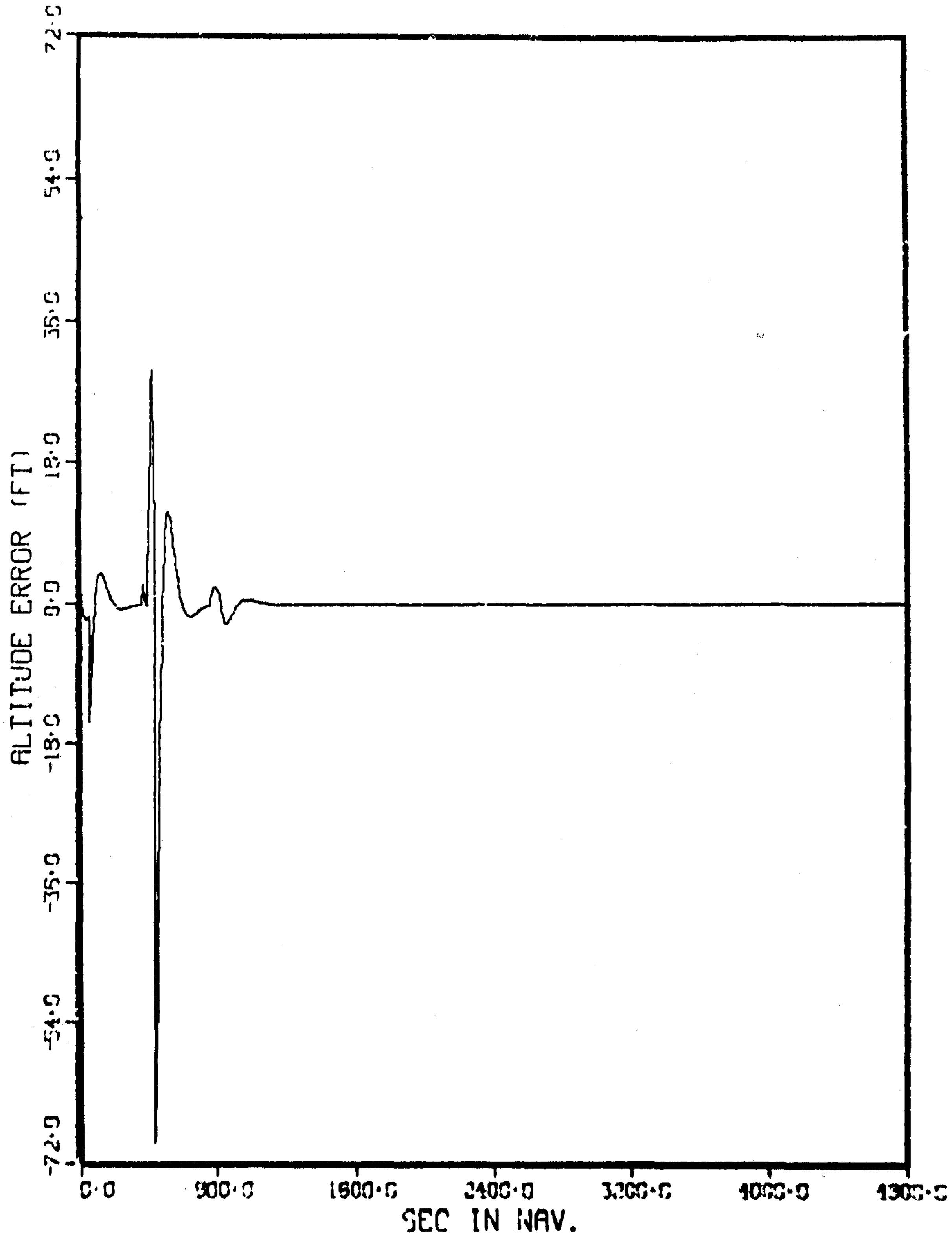
Δ between Base and Full   Plot #70

LONG F4 RUN FULL S/W SEQ 17

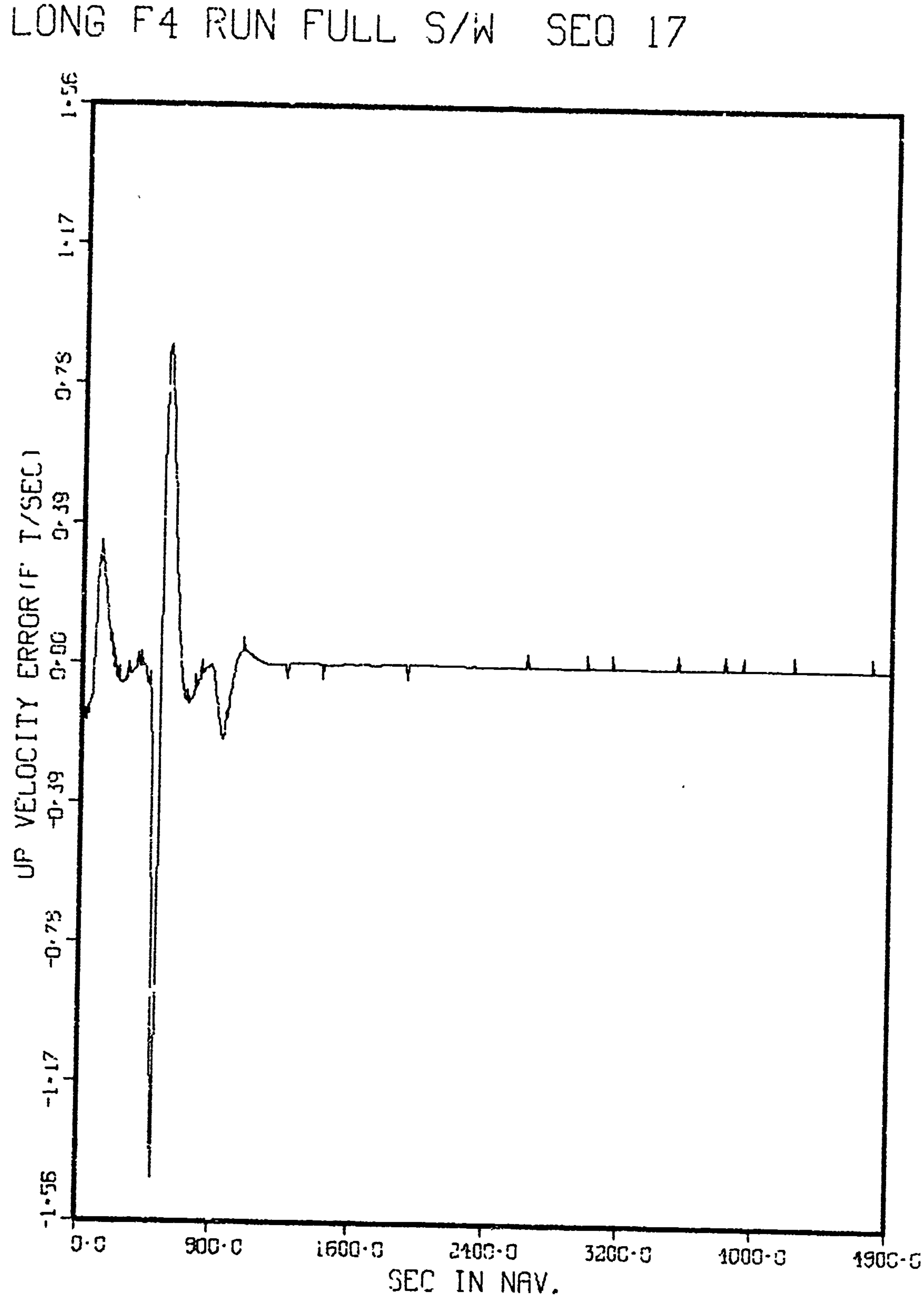


Δ between Baro and Full Plot #71

LONG F4 RUN FULL S/W SEQ 17



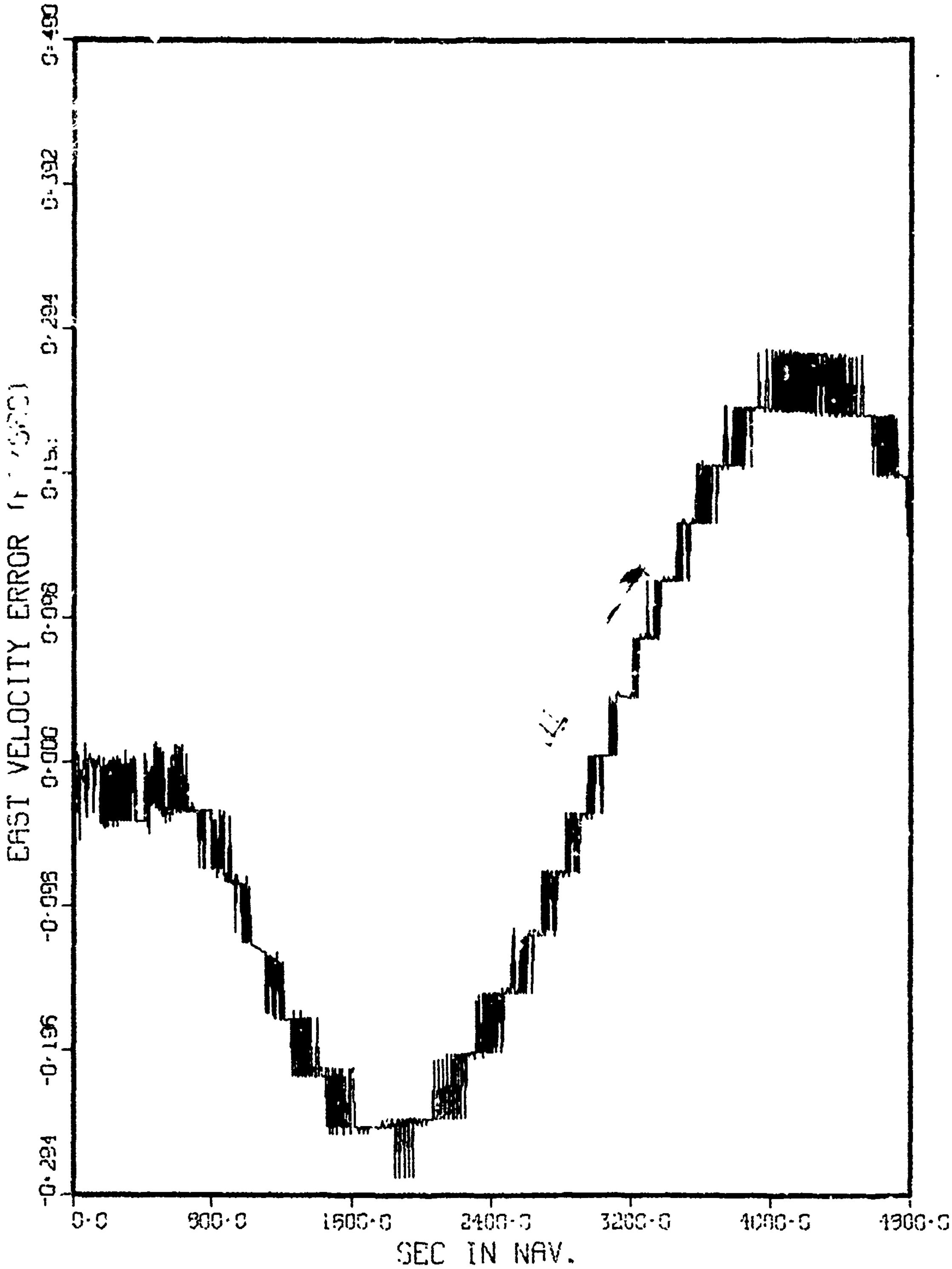
Δ between Base and Full Plot #72



Δ between Base and Full

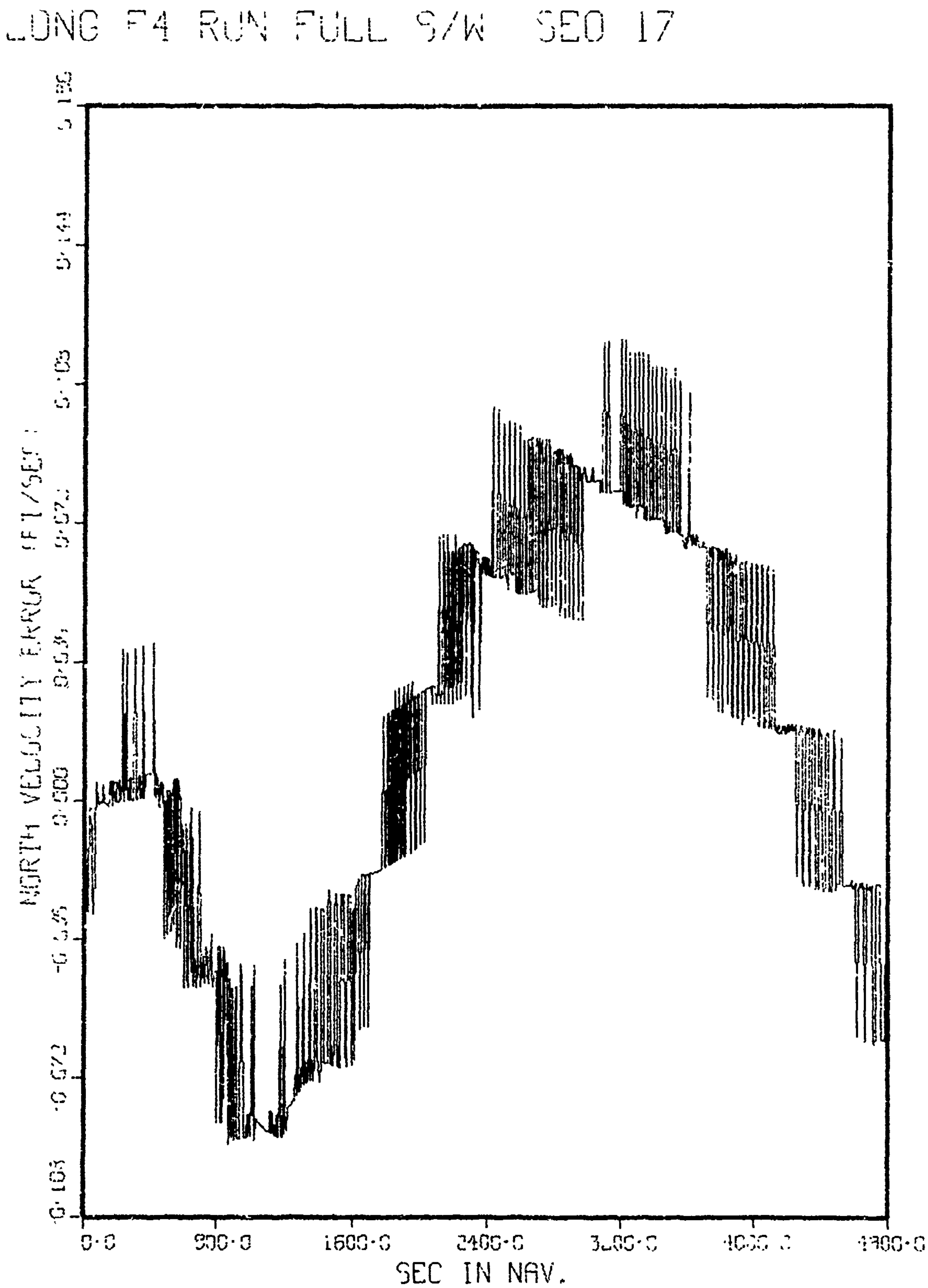
Plot #73

LONG F4 RUN FULL S/W SEQ 17



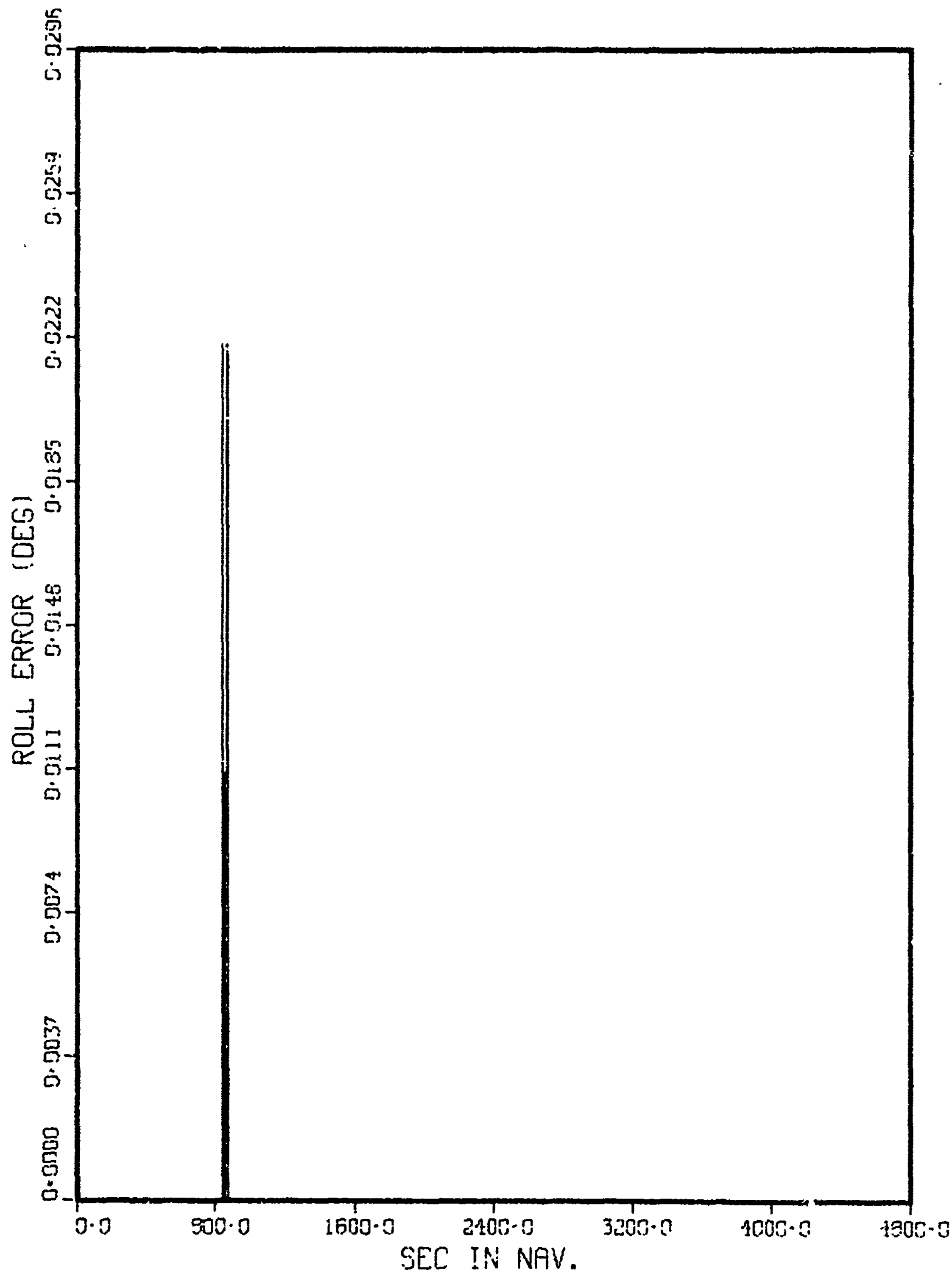
Δ between Base and Full

Plot #74



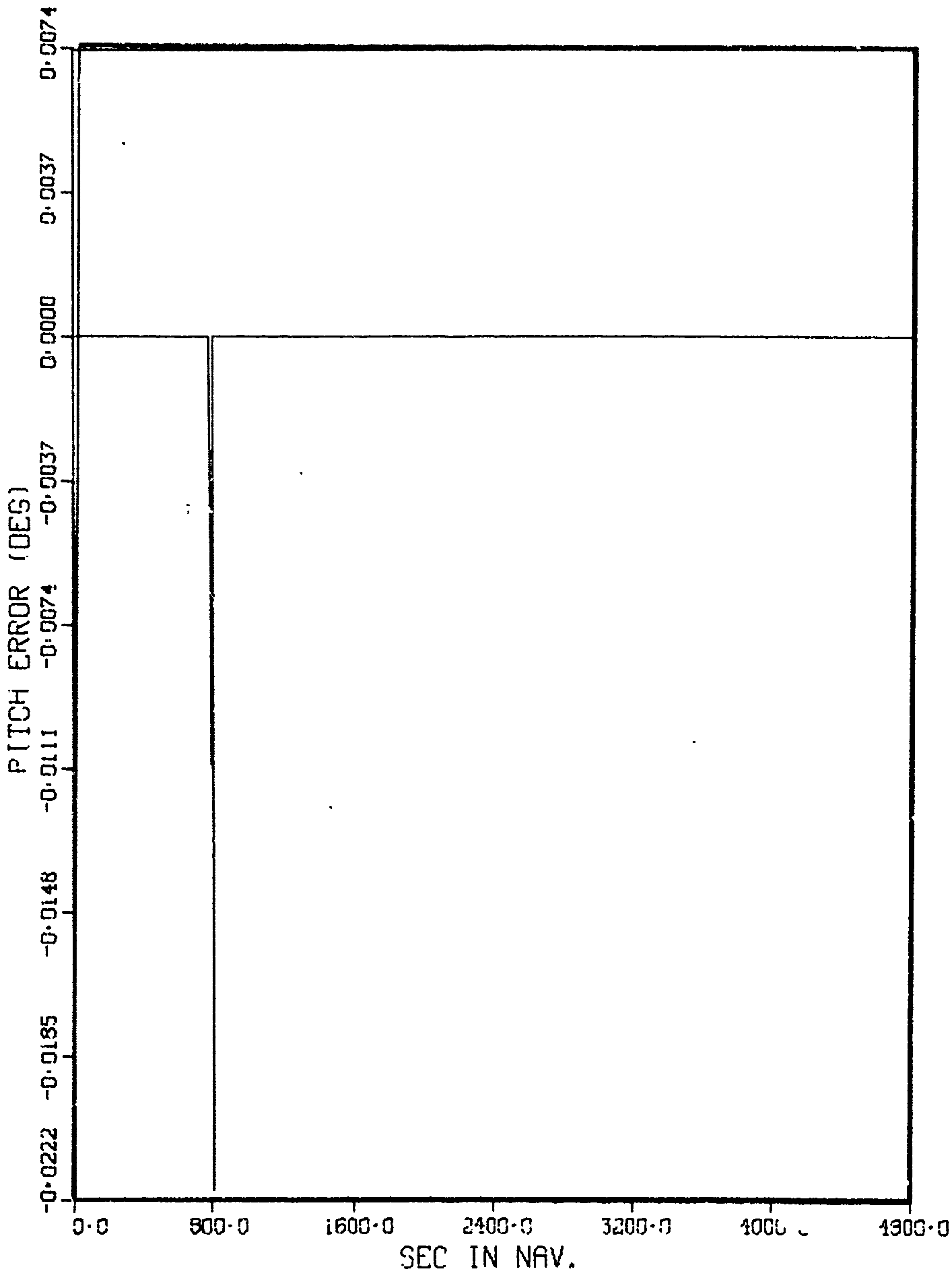
Δ between Bore and Fell Plot #75

LONG F4 RUN FULL S/W SEQ 17

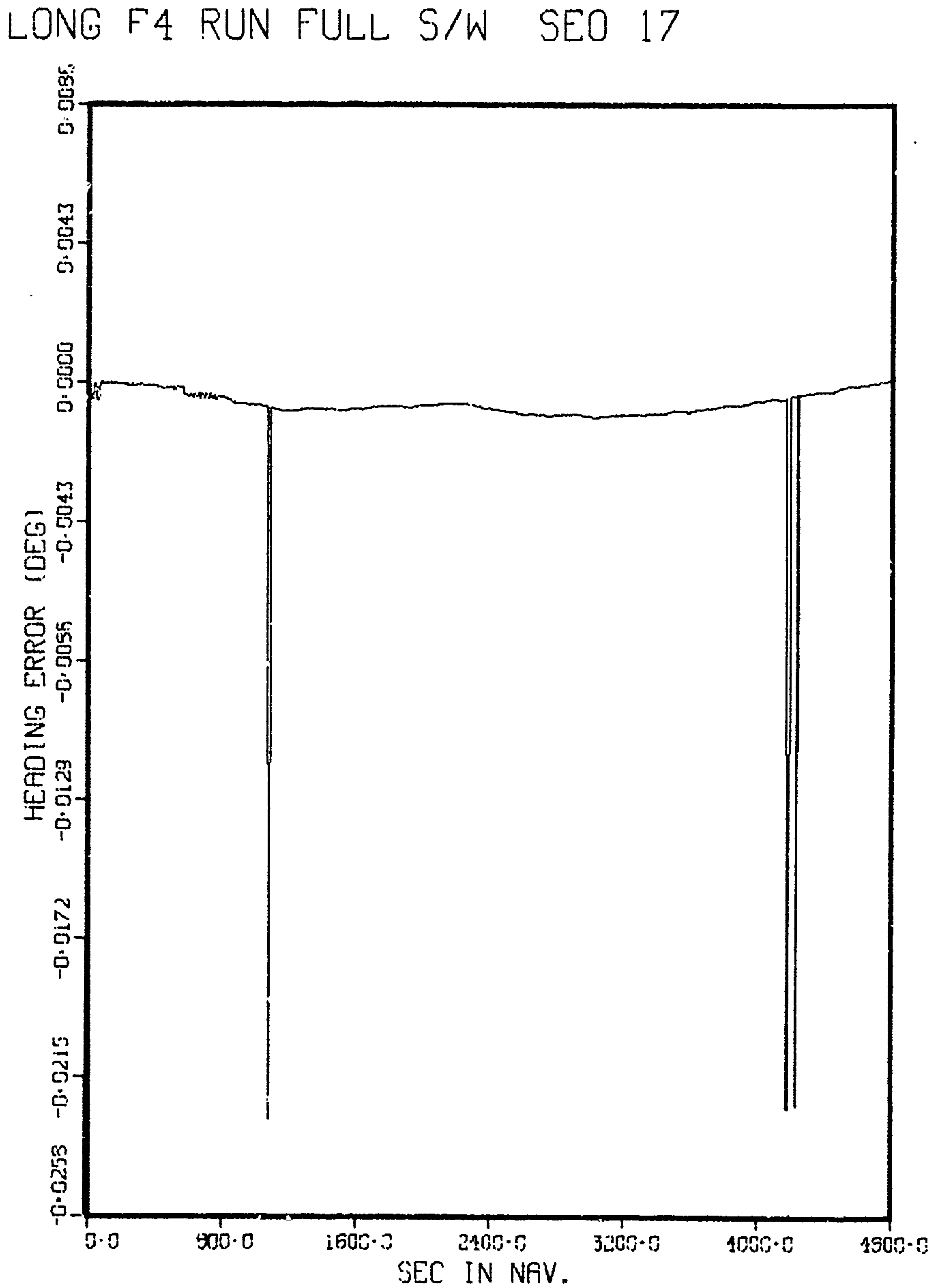


Δ between Bose and Fell   Plot #

LONG F4 RUN FULL S/W SEQ 17



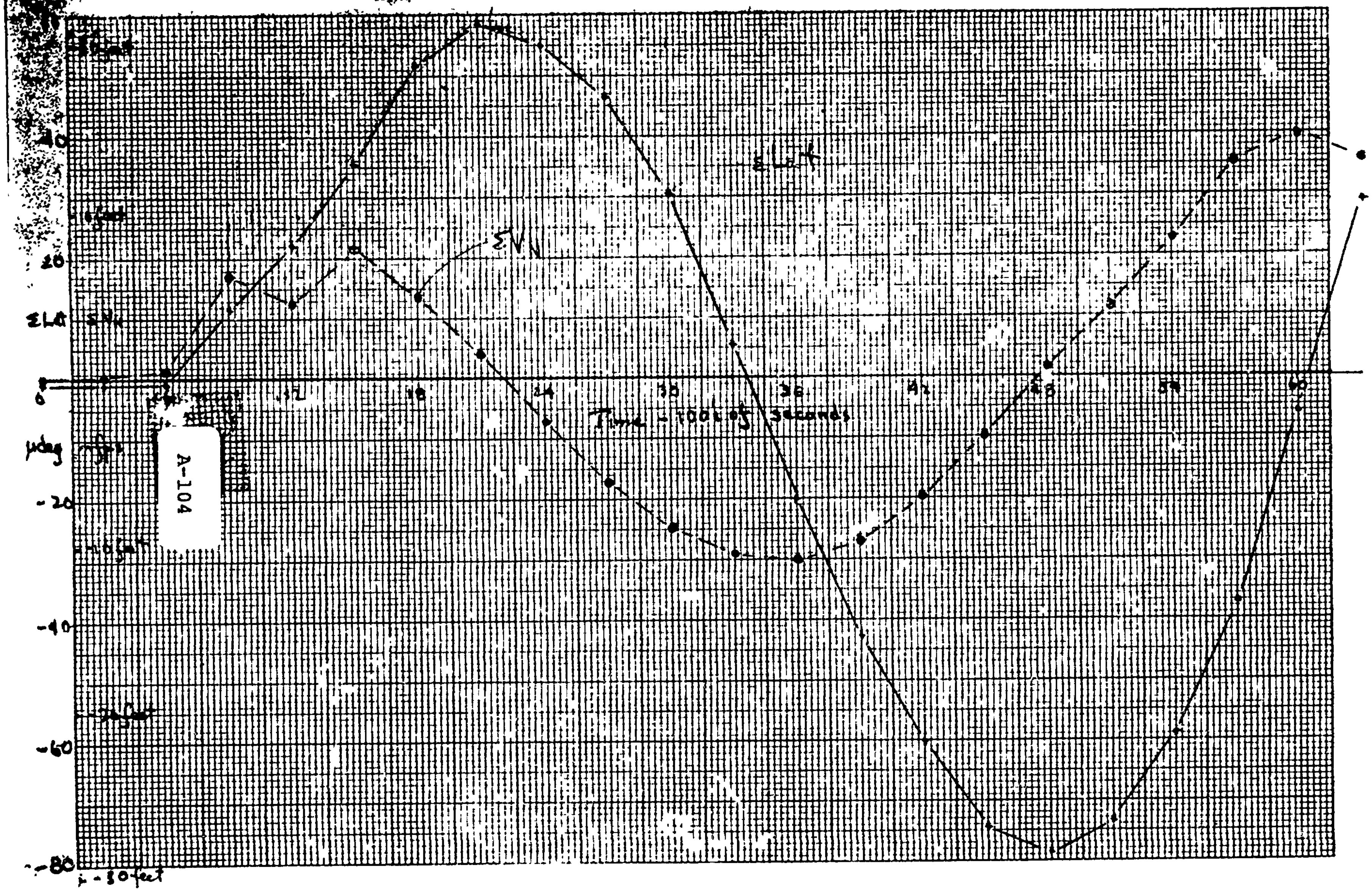
Δ between Base and Full   Plot #77



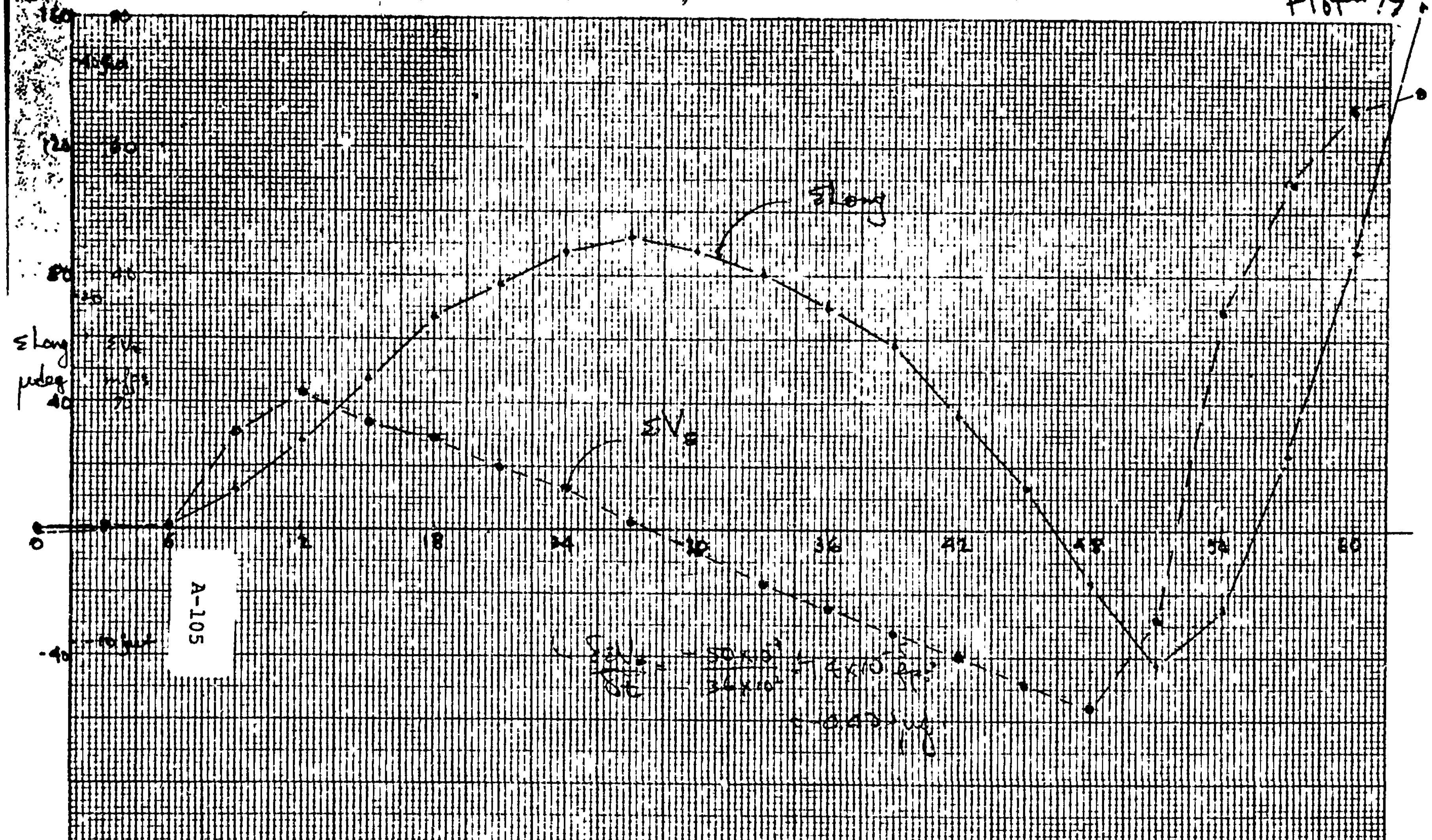
ASTM, 24 bits, 4 Hz, start at 0, improved DCM

16 Jul 76

Plot #78



VUMSIN 24 bits, 4 Hz, Start at 0, improved Def'n 16 Jul 76
Plot #79

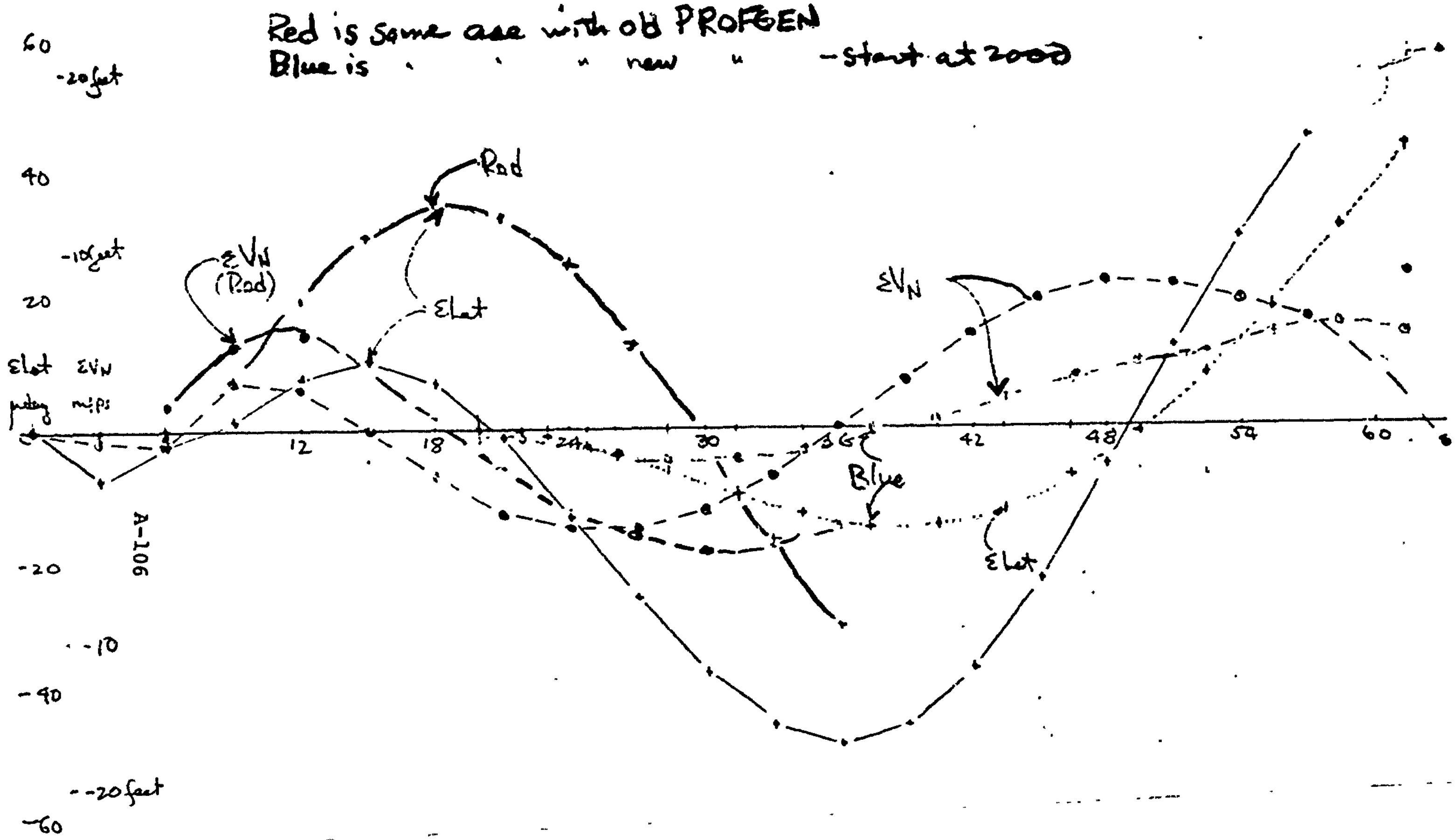


19 Jul 76

NUMSIM, 16 Hz, FSW, N quant, ortho every 16 c.c., 0–6300 sec, New PROFGEN

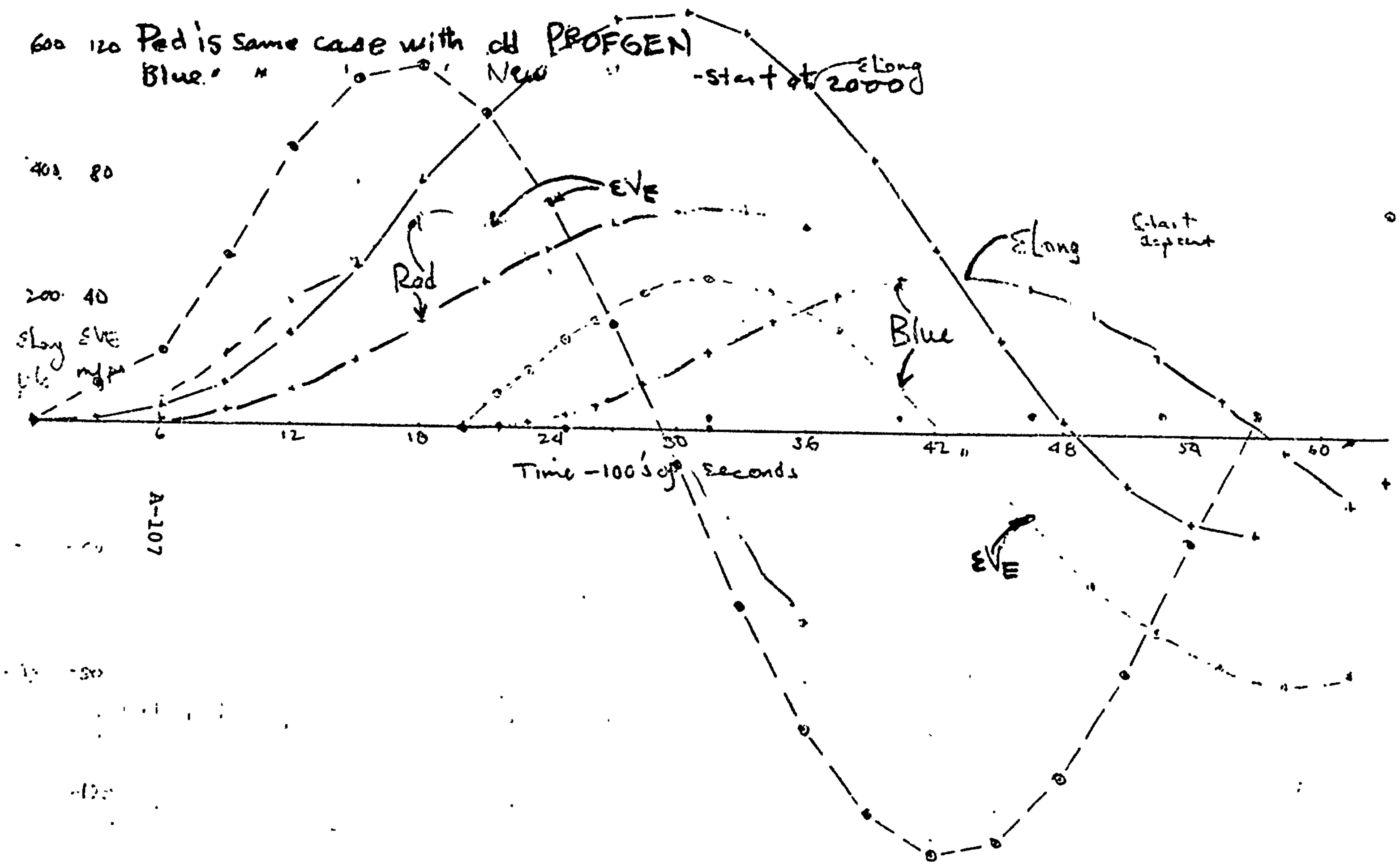
Plot #80

Red is same case with old PROFGEN
Blue is " " " new " – start at 2000



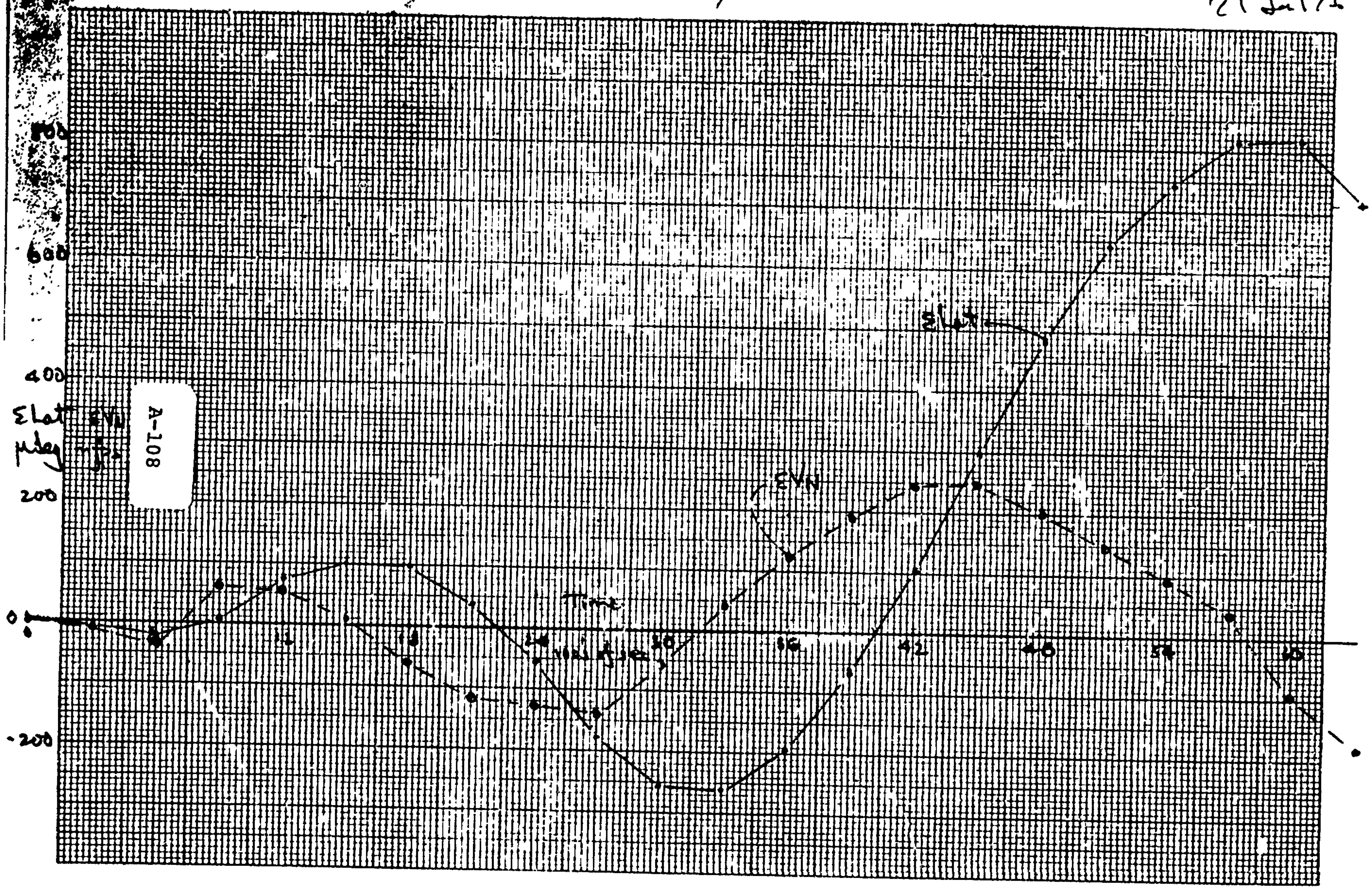
NUMSIM, 16Hz, No quant, est. every 16 c.c., 0-6300, New PROFGEN

Plot #81
19 76



A-107

NUMSIM 24(…) bits, 4 Hz, ortho every 16 cc, 0-4300 sec, quant, new PROFGEN Plot #82
Euclid SW
21 Jul 71

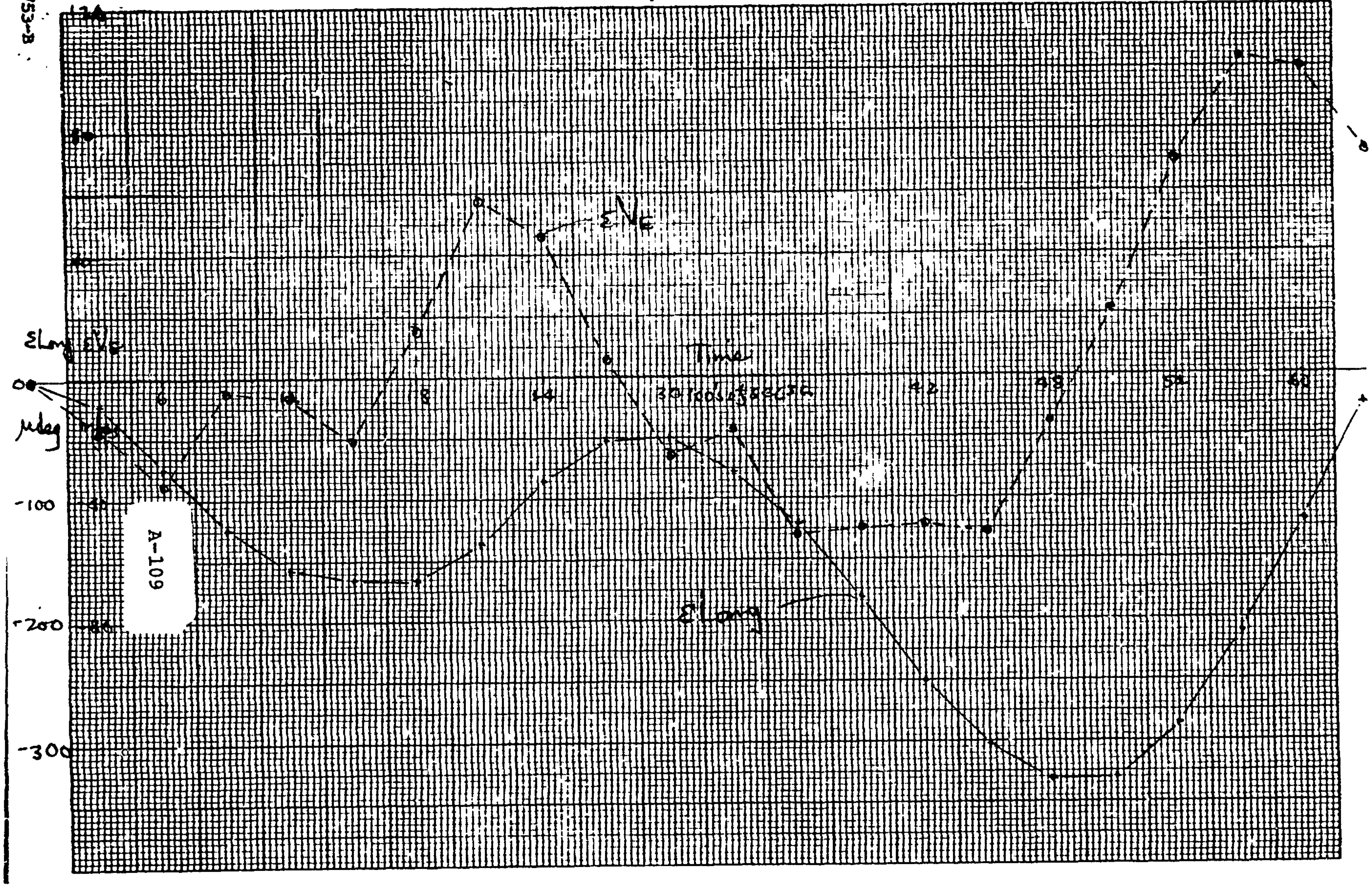


A-108

VUM8JM, 24(&32) bits, 4 Hz, ortho every 16cc, a6300 sec, quant., new PROFGEN Plot #83

Fa Pl SW

21 Jul 76



A-109

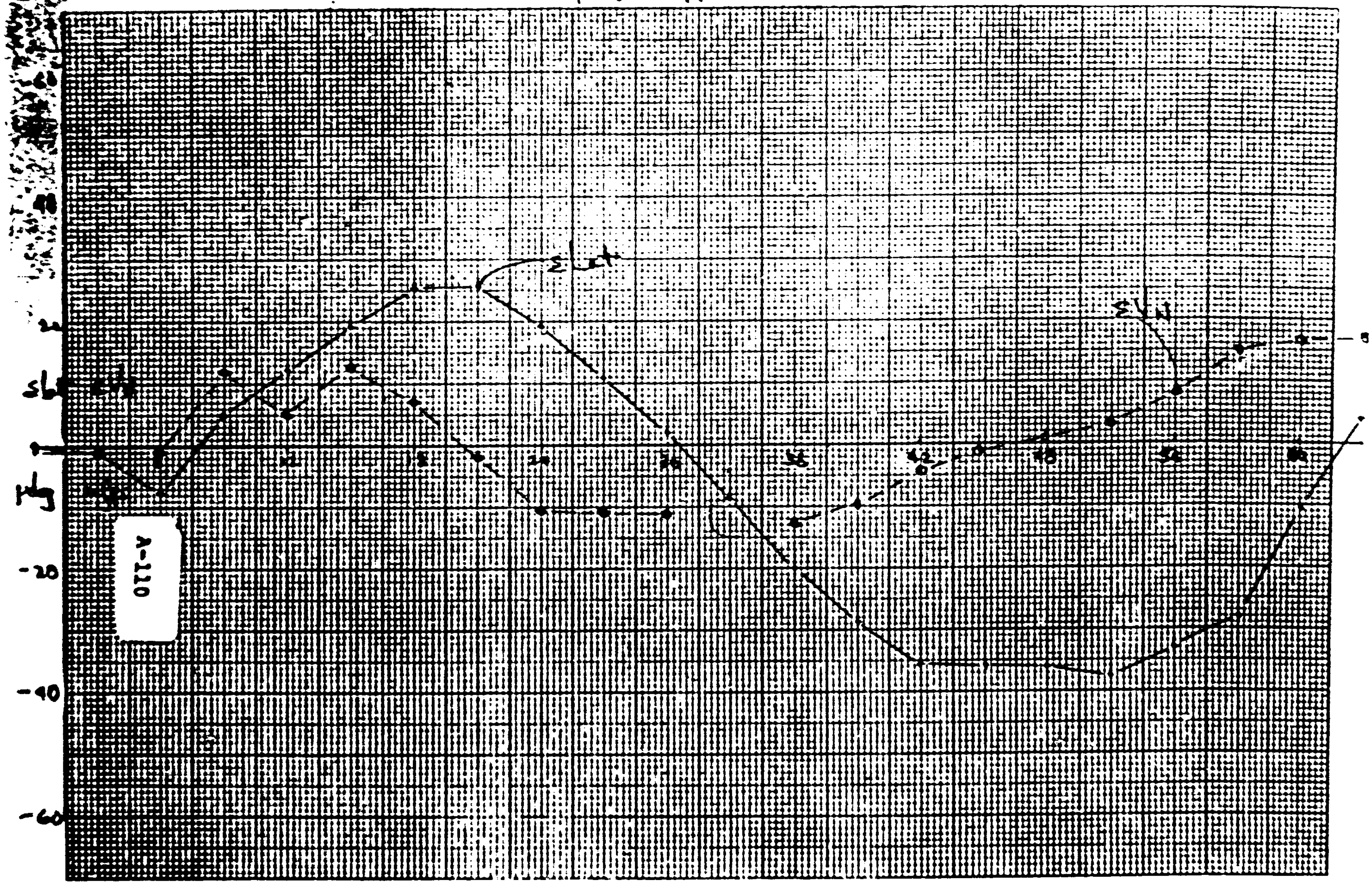
TP 19753-B

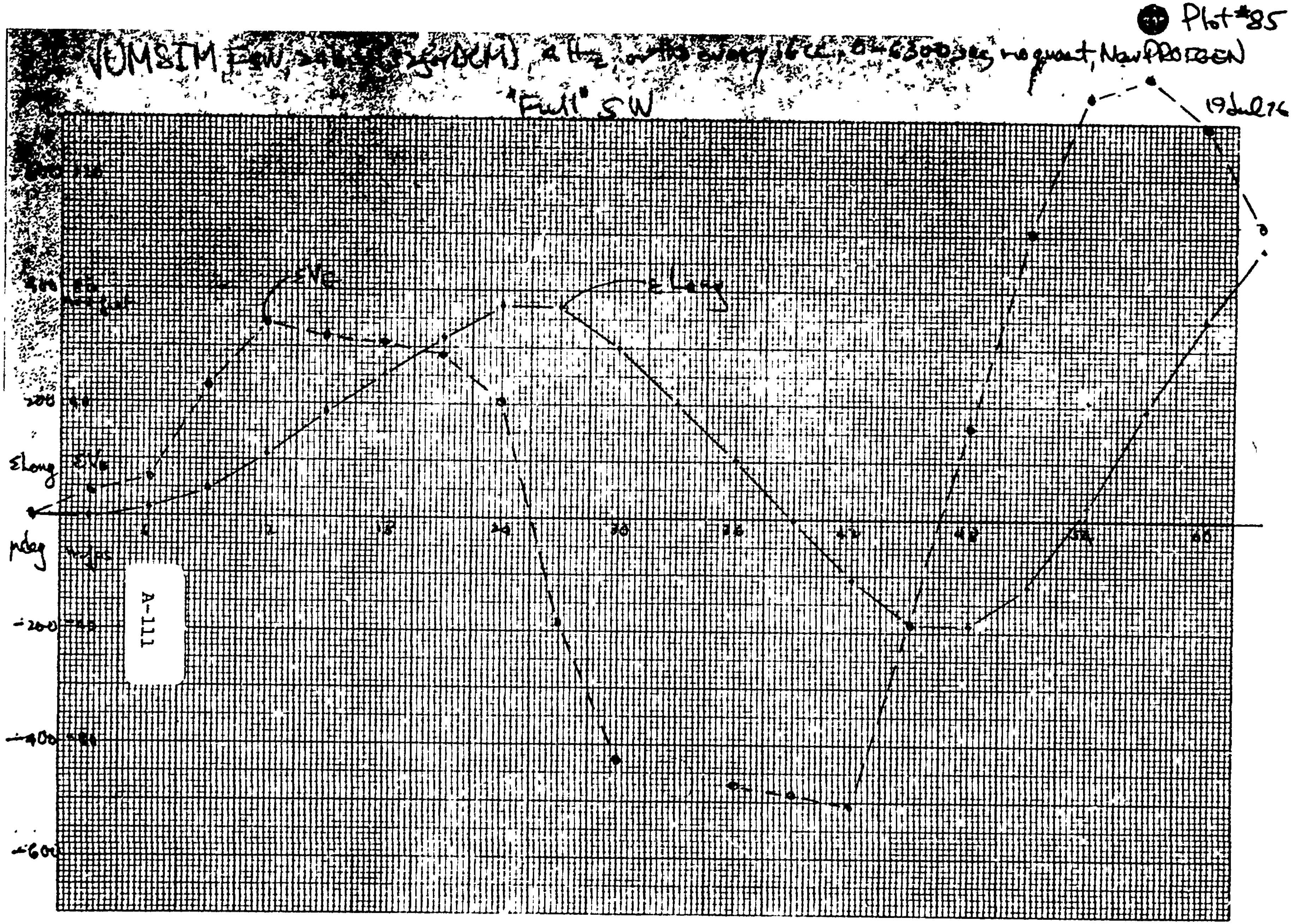
Plot #84

VUMSTM (24 bd (3 for DCM) 4 H$_2$ ortho every 16 cy 0-6300 ..., no quant, new PROFGEN

Fill SW

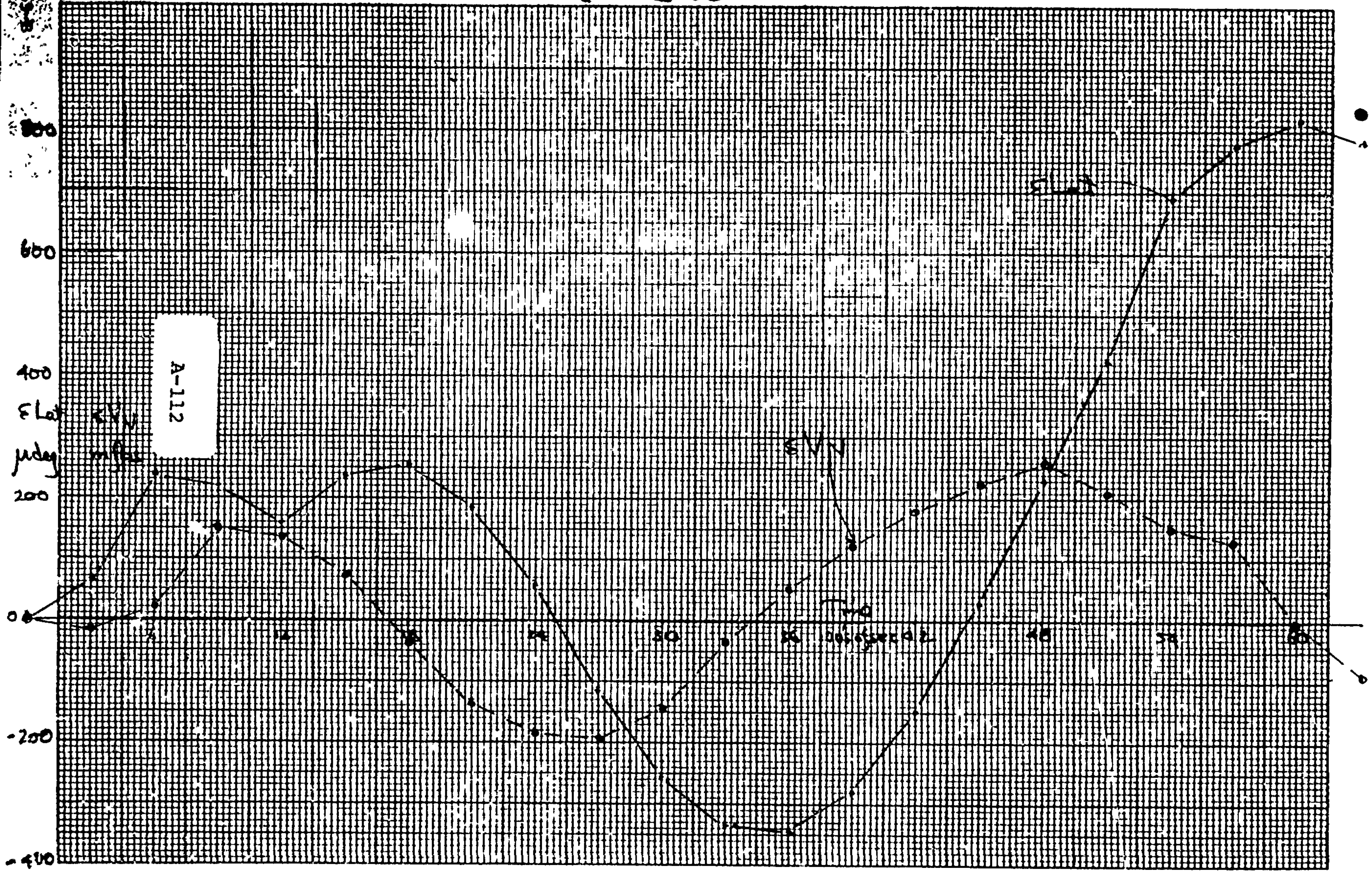
19 Jul 76



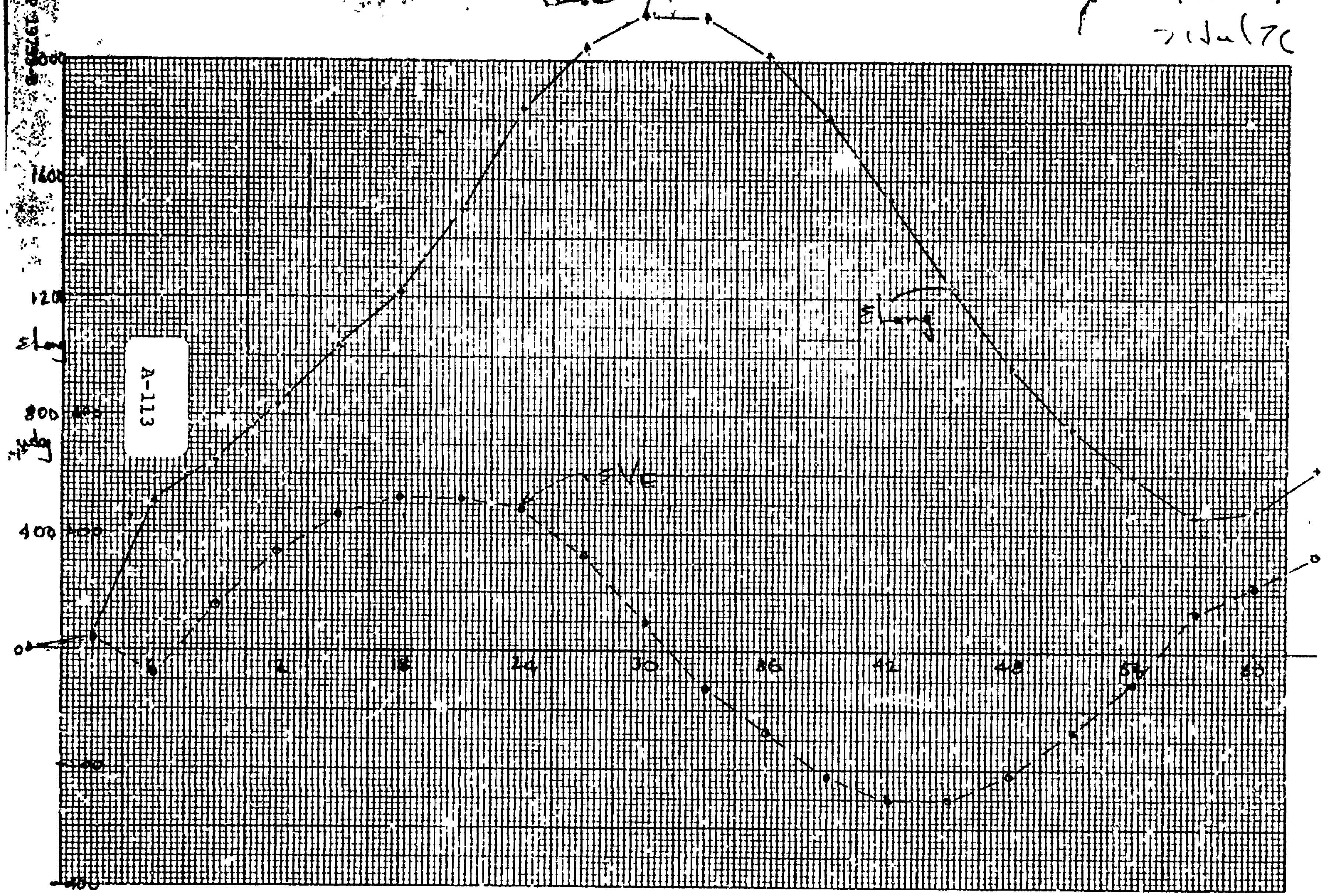

Plot #85
19 Jul 76
"Full" SW
ΣVs
ΣLong
μdeg
200
-200
-400
-600
4
12
18
24
30
36
42
48
54
60

NUMSIM, 24(~~32~~ bits), 4 Hz, no ortho, 0 - 6300 sec, quant., new PROFGEN — Plot #86, 21 Jul 76

Base SW



V L SIM, 24 (32 bits) 4 Hz, no att, 0-6300 sec, quant, new HRØ1 ON
Base S/W
Plot #87
7 Jul 70



A-113

R-977

Addendum

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